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Dams: Effects of Hydrological Infrastructure on Development

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Abstract

Hydrological investments, particularly irrigation dams, have multiple potential benefits for economic development. Dams also have financial, environmental, and distributional impacts that can affect their benefits and costs. This article reviews the evidence on the impact of dams on economic development, focusing on the levels and variability of agricultural productivity, and its effect on poverty, health, electricity generation, and flood control. We also review the evidence on irrigation efficiency and collective action of dam maintenance. Throughout the discussion, we highlight the empirical challenges that restrict the body of causally interpretable impact estimates and areas in which the evidence is particularly thin. We conclude with a discussion of emerging issues pertaining to the long-term sustainability of dams' impacts and suggest directions for future research.

1. INTRODUCTION

Large-scale hydrological infrastructure has played a central role in the history of economic development, as dams can have far-reaching impacts on multiple dimensions of human welfare. Dams can help increase agricultural production by controlling the supply of irrigation water to crops, protect production from climatic risk, help generate electricity, and reduce the risk of potentially disastrous river floods. However, these potential benefits may not be realized for a variety of technical, economic, and behavioral reasons. The benefits may be unevenly distributed and, for some, potentially overshadowed by the harm dams can cause.

The evaluation of the welfare effects of investments in dams is therefore not nearly as straightforward as a purely technical simulation might suggest. From a project evaluation perspective, hydrological infrastructure also carries high costs in terms of the built infrastructure and the maintenance required to manage a dam, but also indirectly through environmental effects that include silting and salinity, health effects from water-borne illnesses, and community resources required to manage irrigated areas. Hydrological investments inherently carry unequal distributions of benefits and costs, particularly relative to whether impacts are measured upstream versus downstream and among those who do and do not directly benefit from water control.

It is therefore not surprising that dams can be controversial due to the political economy of their design, construction, management, redistributive impacts within communities, and ecological footprint. This controversy makes it important to empirically and reliably estimate both the benefits of dams for economic development and their external costs, particularly given environmental changes that may increase global water scarcity in the future.

Measuring the direct and spillover benefits and costs of dams is econometrically challenging. Impact estimates from observational data that address sources of selection bias are remarkably scarce. Hydrological investments are made in geographically favorable topographies and inherently with dialogue, not necessarily equal, between local communities and project planners that may influence the distribution of benefits and costs. Endogenous project placement introduces selection bias in estimates between dam beneficiaries and nonbeneficiaries defined at the individual, household, or community level. The internal validity of impact estimates is challenged not only by selection bias but also because hydrological infrastructure impacts accrue over long time horizons under uncertainty and over large spatial extents. Attrition, noncompliance, and indirect spillovers can bias impact estimates over longer time horizons of the dams' expected life.

Due to the complex political economy of large-scale community-based projects and their often uncertain returns, the funding and construction of hydrological investments have varied over time and region, though all areas of the world have seen significant hydrological investments. In the past decade, the World Bank has increased funding after almost a decade of limited engagement in large-scale hydrological investments.[1] There has also been considerable investment by national governments in Bangladesh, Brazil, China, Mexico, India, Indonesia, Tunisia, and Pakistan, among others, as well as by regional development banks[2] and agricultural donors [e.g., the Food and Agricultural Organization of the United Nations (FAO) and International Fund for Agricultural Development (IFAD)]. **Figure 1** provides an overview of land irrigated globally and the sources of irrigation.

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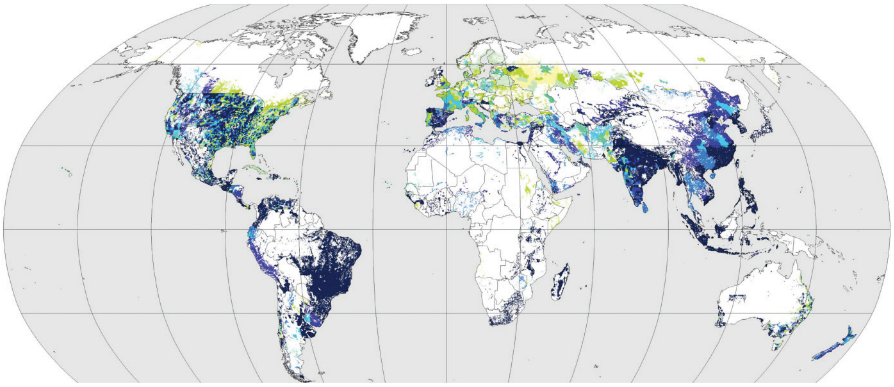
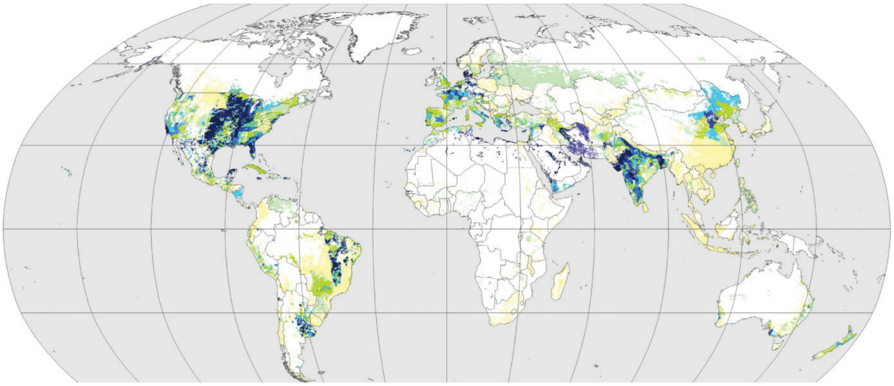
[1] World Bank withdrawal from hydrological investment has been linked to social and environmental policy violations in the construction of the Sardar Sarovar Dam on the Narmada River in India in 1994 (Bosshard 2015).

[2] Regional development banks with higher irrigation financing portfolios include the African Development Bank, Asian Development Bank, China Development Bank, Development Bank of Japan, Inter-American Development Bank, and the Latin American Development Bank.

a Area actually irrigated



b Area irrigated with groundwater



c Area irrigated with surface water

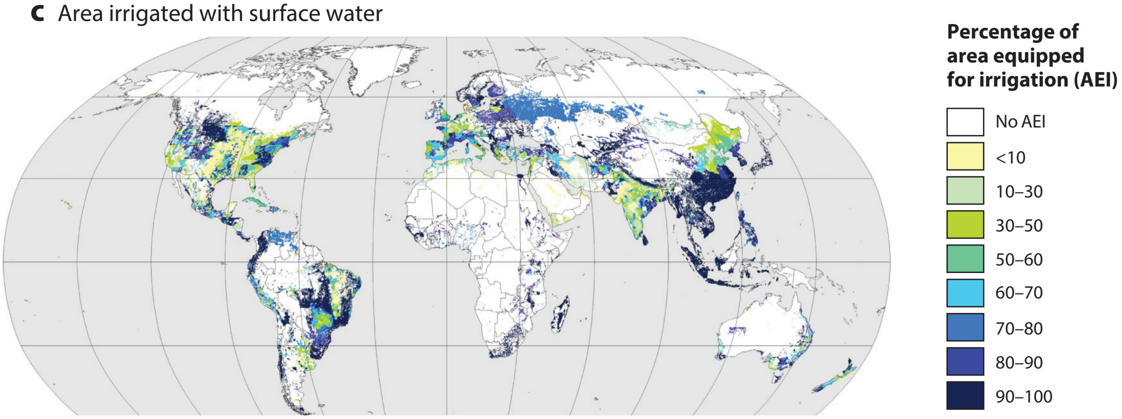


Figure 1

Digital global map of irrigation areas, October 2013. The maps show the percentage of area equipped for irrigation that is (*a*) actually irrigated, (*b*) irrigated with groundwater, or (*c*) irrigated with surface water. For most countries, the base year of statistics is in the period 2000–2008. Robinson map projection, resolution of 5 arc minutes. Created by Stefan Siebert and Verena Henrich (Institute of Crop Science and Resource Conservation, University of Bonn, Germany); Karen Frenken and Jacob Burke (Land and Water Division, Food and Agriculture Organization of the United Nations, Rome, Italy). Figure adapted with permission from **http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm**.

Investments in large-scale irrigation have been linked to increasing agricultural productivity and structural transformation during the Green Revolution (Evenson & Gollin 2003, Johnson et al. 2003). More recent investments may also be motivated as a key climate change adaptation strategy (Molden 2007; World Bank 2009; Olmstead 2014; IPCC 2014, 2018).

This article is organized to provide an overview of the effects of dams from these multiple perspectives and econometric challenges to the internal validity of these impacts.[3] The second section provides a theoretical motivation of the ensuing review of the evidence. Section 3 reviews challenges to the estimations of direct and spillover effects of hydrological investments. Section 4 summarizes our understanding of the existing evidence of the impacts of dams on agricultural production, input use and costs, poverty, health, and flood risk. Section 5 discusses some of the constraints faced by centralized hydrological infrastructure, especially in an era of water scarcity and mounting environmental concerns. The last section concludes by reflecting on future research as well as gaps in the literature.

2. THEORETICAL MOTIVATION

In this section, we present a brief theoretical outline of the benefits that dams can provide to downstream users, focusing, as does the literature, on benefits related to irrigation supply and agricultural production. We separate the discussion between impacts on the mean level of productivity and income and impacts on its variability, which are central to irrigation.

2.1. Impacts on the Level of Agricultural Income

The core benefit that access to irrigation from dams can offer farmers is the ability to supplement precipitation-derived sources of water for their crops with an alternative, potentially more reliable water source. In circumstances that are widespread in developing countries, control of the water supply can help farmers overcome severe constraints to cultivation associated with precipitation variability, uncertainty, and either deficiency or excess. Access to a controlled source of water can affect the production possibilities of farmers through multiple pathways.

The first is the potential improvement in productivity of cropping systems that can also be practiced under rainfed conditions but are water constrained. Irrigation can, in principle, overcome deficiencies in both the total amount of precipitation and its intraseasonal temporal distribution that reduce yields or revenue in such systems. For example, supplying crops with irrigation water during dry spells in the rainy season—prolonged periods of insufficient rain are common in the semiarid tropics—can protect crops from adverse impacts. Similarly, irrigation can offer farmers the ability to choose optimal planting dates without regard to the timing of the onset of seasonal rains, with potential benefits for both yields and market prices. Irrigation can also boost the productivity of dry season cultivation that is otherwise solely reliant on soil moisture accumulated during the preceding rains, which can be insufficient for crops' water requirements.

Access to irrigation can also help farmers practice cultivation that would not otherwise be possible. During the rainy season, irrigation can enable the cultivation of more water-intensive (and productive) crop varieties, or altogether different (and more valuable) crops that require greater quantities of water or a more regular water supply or that are prohibitively sensitive to water deficiencies. Irrigation can also enable cultivation during dry periods of the year, when both rainfall and soil moisture are scant, thus enabling a second or a third crop per year, often referred

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[3] As stated above, the primary focus of this review is large-scale dams. We discuss irrigation because most dams serve irrigation purposes and thus restrict our discussion of irrigation to contexts of surface water irrigation, mainly through large-scale structures.

to as an increase in cropping intensity. In many developing countries, annual cropping calendars consist of one or two wet seasons of limited durations, and land remains fallow for major parts of the year. In such circumstances, increases in cropping intensity may offer the largest gains in production.

In principle, irrigation also has the potential to help crops overcome heat stress through increased evapotranspiration. This benefit could become increasingly important as a climate change strategy.

From an agronomic point of view, it is therefore clear that the ability to control water supply to crops should have substantial benefits for agricultural productivity. In practice, however, this potential may fail to be fully realized for a number of reasons. Empirical evaluations of the impacts of irrigation in real settings are therefore important to conduct as a supplement to agronomic trials conducted in controlled conditions. In addition, the return on irrigation investment is composed of the net benefits and also the net costs. Increased agricultural productivity is therefore not a sufficient condition for higher profitability.

To fix ideas, consider an annual agricultural profit function:

$$\pi_t = \pi_t(\mathbf{V}_t, W_t; \theta, \boldsymbol{\rho}) = Q(\mathbf{V}_t, W_t; \theta, \boldsymbol{\rho}) - \upsilon\mathbf{V} - \boldsymbol{\omega},$$

represented here as the value of production Q, net of the costs of all inputs, including irrigation. Production is represented by a standard function that depends on vectors of inputs that include fixed assets, land, agrochemical inputs, and farm labor ($\mathbf{V}_t$) and is subject to the choice of agricultural practices ($\boldsymbol{\rho}$) and seasonal climate variability (θ). We explicitly include the supply of irrigation water W_t as an input to production. This input represents the accumulated flow of water to the plot from all irrigation sources (sometimes called blue water in the hydrological and agricultural literatures) but excludes precipitation and naturally occurring soil moisture (sometimes called green water in the hydrological and agricultural literatures). In the absence of irrigation, $W_t = 0$. This simple production function abstracts away from the intra-annual distribution of weather and the supply of irrigation and embodies the gains from increased yields, multiple cropping, and crop portfolio changes that may occur due to increased water control. Production costs include the costs of all inputs $\mathbf{V}$ and the costs of irrigation $\boldsymbol{\omega}$, which can differ depending on whether they are borne by farmers or public institutions, and need not necessarily be proportional to the amount of water used.

The gains from irrigation are the difference between profits realized when irrigation water is provided to the farm and the profits that would have occurred on the same farm if no irrigation water had been supplied, i.e., $W_t = 0$. Note that a farmer's decision on whether to make use of irrigation is not driven by productivity changes, but by profitability changes, despite the justification of many dam investments based on changes in agronomic returns.

The ideal gains from irrigation are realized when the supply of irrigation water is unrestricted and fully satisfies crops' water requirements, and an optimal adjustment of all other inputs and practices is made to account for irrigation. These ideal gains are unlikely to be realized in the farms of most smallholders. However, they can be approximated by crop model–based simulations or controlled experiments in agronomic research farms, which are sometimes used to predict the benefits of irrigation projects. They therefore serve as a useful benchmark against which actually observed gains can be compared.

In real settings, the gains from irrigation may differ from the ideal gains for several reasons. First, the actual amount of water that is supplied to a farm may, and in fact is very likely to, differ from the unconstrained amount. In the case of irrigation dams, water supply is often highly constrained by a range of complex hydrological, institutional, and geographical factors that mostly lie outside the control of the farmer. Merely having access to an irrigation facility does not usually entail unconstrained access to water. Water supply may be limited in quantity, intermittent, unreliable, poorly suited to the agricultural calendar, and unequally distributed between upstream and downstream users along canals. The extent of the benefits provided by such a constrained supply of water is therefore hard to evaluate on the basis of idealized agronomic projections.

Second, in response to the supply of irrigation water, farmers may not necessarily optimally adjust the application of other inputs or their agronomic practices. For example, when water-related constraints to crop growth are relaxed through irrigation, the returns to the use of fertilizer may increase. But a number of possible constraints, unrelated to irrigation, may prevent the farmers from increasing the application of fertilizers. Such constraints are discussed at length in the extensive literature on the adoption of improved technologies in smallholder agriculture (Foster & Rosenzweig 2010, Magruder 2018), and they are not unique to dam irrigation. For example, water stress may not necessarily be the binding constraint on crop yields. In some cases, deficiency in other inputs that are strongly complementary to water could limit the benefits of supplying additional water. One of the crucial achievements of the Green Revolution was to develop crop varieties that, unlike traditional varieties, could utilize increased water (and nitrogen) availability for greater caloric output. Various other forms of biotic and abiotic stress or nutrient deficiencies can also constrain yields. Limitations in either input or output market access may also prevent farmers from translating increased production into higher revenues. Mismanagement and incorrect practices by farmers can also result in failures to realize irrigation's full benefits, as observed in expert-operated trials.[4]

Third, the cost of irrigation water may not be borne by users, i.e., farmers, leading them to choose the amount of water used at an individually optimal level that nevertheless is socially suboptimal. In the case of dam-based irrigation, it is particularly rare for farmers to bear the true cost of irrigation water, especially in developing countries.

2.2. Impacts on the Variability of Income

In addition to its impact on mean productivity, an extremely important benefit offered by irrigation is the potential ability to stabilize production across years. It has long been appreciated by development economists that low-income households in developing countries, especially those employed in agriculture, are often subject to enormous production risk and interannual variability in output. Much of this interannual variability is likely due to variability in precipitation, and numerous studies have found correlations between rainfall (and other weather) shocks and a range of socioeconomic outcomes. The supply of irrigation water to crops therefore has the potential to reduce production risk. Like any strategy for smoothing production across years, this is likely to have numerous welfare benefits, including smoothing consumption and reducing transient forms of poverty, avoiding the costs of other consumption-smoothing strategies, and increasing investments in the farm.[5] In addition, as pointed out by Gemma & Tsur (2007), since agricultural

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[4] The net result is that the actual gains from irrigation $\Delta\pi$ are diminished from their potential $\underline{\Delta\pi}$ by an amount that represents a "performance gap." Formally, we can define the performance gaps as $\Delta\pi = \underline{\Delta\pi} - [\pi(\underline{\mathbf{V}}, \underline{W}; \theta, \underline{\boldsymbol{\rho}}) - \pi(\underline{\mathbf{V}}, \underline{W}; \theta, \underline{\boldsymbol{\rho}})]$. We may write the ideal gains formally as $\underline{\Delta\pi} - \pi(\underline{\mathbf{V}}, \underline{W}; \theta, \underline{\boldsymbol{\rho}}) - \pi(\mathbf{V}_0, W_0 = 0;\ \theta, \boldsymbol{\rho}_0)$, where the under bar represents the optimal amount applied not only of water, but of all other inputs conditional on the ideal supply of water. In contrast, the 0 subscript refers to the use of inputs and practices under unirrigated conditions.

[5] Reducing production risk can help farmers smooth consumption across years, especially in contexts in which other consumption-smoothing mechanisms have limited efficacy, such as when production shocks are idiosyncratic (as is common in the case of drought). Because poverty is now increasingly considered to be a transient

production is a concave function of stochastic water supply (e.g., from precipitation), the ability to stabilize water supply through irrigation will not only reduce the interannual variance of production, but it will also increase its mean value.

Formally, the long-term, expected mean gains in production are

$$E(\Delta \mathrm{Q}) = E[\mathrm{Q}(W, \theta)] - E[\mathrm{Q}(W = 0, \theta)],$$

where the expectations are taken over time (ignoring discount rates and other inputs for simplicity), and we have kept only irrigation water and weather (precipitation) in the production function. Assume that production is a concave function of overall moisture availability for the crop, which is a combined function of water delivered by irrigation and by precipitation with a high degree of substitutability. With perfect substitutability, $\mathrm{Q} = \mathrm{Q}(W + \theta)$, we have

$$E(\Delta \mathrm{Q}) = E[\mathrm{Q}(W + \theta)] - E[\mathrm{Q}(\theta)].$$

One form of an ideal supply of irrigation water is to keep the total supply of moisture at a constant level each year so that always $W + \theta = r + d$. Here, $r = E(\theta)$ is the mean level of rainfall across years, and d is the additional amount of water. In this case, we can decompose

$$E(\Delta \mathrm{Q}) = E[\mathrm{Q}(r + d)] - E[\mathrm{Q}(\theta)] = [\mathrm{Q}(r + d) - \mathrm{Q}(r)] + \{\mathrm{Q}[E(\theta)] - E[\mathrm{Q}(\theta)]\}.$$

The overall gains from irrigation to expected production are the sum of two parts: The first one represents the difference in production between moisture provided by mean rainfall and that which is provided by irrigation, $r + d$. The second part is the difference between production at the mean level of rainfall and the mean level of production from variable rainfall. By Jensen's inequality, since Q is concave, this is strictly positive. Gemma & Tsur (2007), whom we have followed here, define these two terms as the augmentation value and stabilization value of irrigation.

In practice, however, irrigation may not be able to deliver the required supply of water to ensure moisture remains constant. As a result, the theoretical potential of irrigation to stabilize crop production may be limited in realistic settings. It is important to remember that the supply of water delivered through irrigation infrastructure is itself subject to stochastic variability. This is especially true for surface irrigation projects with finite storage, whose water supply is, to some extent, determined by precipitation in their catchment. It is not uncommon for even a single year of drought to constrain water release from major irrigation dams. Even if water supply is uncorrelated with local rainfall, it may be highly variable, being determined by other sources of precipitation elsewhere, or by other stochastic factors. In addition, water supply is certainly not the only source of production risk for farmers, so the impacts of irrigation on overall production risk may be quite modest.

2.3. Externalities and General Equilibrium Effects

In typical centralized irrigation systems, the supply of water to farmers' plots—in terms of both amount and timing—is often constrained by factors that are outside their control.

Farmers can still decide whether to use water supplied by the irrigation system, how much of it to use, and for which crops. Theoretically, farmers need not make use of the supplied

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as well as chronic condition, avoiding such consumption shocks is an important poverty eradication strategy. This can also reduce the need to use alternative consumption-smoothing mechanisms, some of which carry substantial costs and losses to mean income. In addition, production risk is considered to be one of the main barriers to increased farm investment and the adoption of improved technologies. Several studies have found evidence to support this thesis (see, for example, Karlan et al. 2014, Emerick et al. 2016).

irrigation at all. In practice, however, it is unlikely that farmers will forgo the opportunity, given the typically very low, if any, costs. In some cases, it is even technically infeasible. We therefore do not emphasize a farmer's decision on whether or not to use the supply of irrigation as central to the theoretical framework. However, farmers may make use of alternative or additional sources of irrigation water. It is not uncommon for farmers served by canal systems in India to obtain water from wells that are themselves recharged by the canals in order to improve control of their water supply. Schoengold & Zilberman (2007) outline multiple models that characterize other features of irrigation decisions, including when farmers have the choice of multiple irrigation technologies or have a dynamic time horizon, as well as the social planner's problem in choosing a hydrological investment's size.

Farmers' decisions on the amount of water to use are affected by the farm-specific factors discussed above, but they can also be subject to externalities. An important feature of centralized irrigation systems is the spatial organization of the flow of irrigation and the resulting externalities between farmers' water use decisions. In particular, upstream users' water use decisions can affect the water supply to downstream users—be they other farmers or nonagricultural or environmental users—in both quantity and quality. Ostrom & Gardner (1993) provide a political economy model of the allocation of water within a large-scale irrigation system and its maintenance in a strategic game where "headenders" and "tailenders" have asymmetric information.[6]

As is the case for any other technology that increases agricultural productivity, widespread use of irrigation can also generate general equilibrium effects, as the impacts of hydrological investments do not accrue only to the farmer or agricultural household. Lipton et al. (2003) discuss general equilibrium effects from irrigation investments on labor markets, input, and output markets that are only indirectly captured in an agricultural household model. From a macroeconomic perspective, these general equilibrium effects could have significant effects on rural migration and the allocation of workers between agricultural and nonagricultural sectors. Increased demand for complementary inputs may cause missing input markets to be created but which also increase farmer costs if national supply constraints are not adequately addressed through agricultural trade policy. The increased production capacity of hydrological investments may reduce farmer revenue if agricultural commodity prices have high volatility tied to seasonality, in the case that storage is unavailable in the supply chain. Low food prices will have higher welfare effects on net consumers than net producers in such economies.

3. METHODOLOGICAL CHALLENGES TO ESTIMATING IMPACTS

We outline methodological challenges to measuring the direct impacts of dams on development outcomes using observational data. Measuring the impacts of hydrological investments is challenging for several reasons. First, the allocation of dam water is likely to be endogenous at scales ranging from the water basin to the individual plot. Second, dams are likely to have impacts that are highly uneven geographically and therefore accrue differently at different scales of analysis. Third, these impacts also accrue over longer time horizons than are often considered in socioeconomic studies. From an empirical point of view, the high degree of likely interannual variability in the gains from irrigation makes it important to observe gains over a multiyear time frame.[7] Lastly, we highlight econometric challenges in the measurement of spillover effects on markets, food prices, and labor market effects.

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[6] See also Baland & Platteau (1997, 1998) for models of inequality in commons management.

[7] This variability can result from variations in both water supply and rainfall. Evaluations based on a single or small number of years may be inadequate, even more so than they are inadequate for other interventions.

Our review of the literature did not yield any randomized evaluations of the impacts of dams. This is not surprising given the logistical and political economy constraints that would arise in creating exogenous variation in land allocation.

A large literature examines the estimation of profit functions, production functions, and input demand functions in agricultural economics (e.g., Chambers 1988, Chambers & Quiggin 2000). The primary identification challenge in the estimation of a profit or production function is the omitted variable bias introduced in the specification when multiple choice variables are components of the production technology modeled. In both profit functions and production functions, a household will choose crop area, fertilizer, seed, labor, and rental capital, assuming land is quasi-fixed. Omitted variable bias may occur if unobservable plot characteristics influence choice variables in an empirical specification. For this reason, estimations of yield effects including an indicator for irrigation are likely to be biased.

Estimates of the effect of irrigation are also likely to be biased by nonrandom placement of irrigation investments and selection bias in the take-up of irrigated plots. Hydrological investments are not made without maximizing the likelihood of project success. Often implicit or intentional targeting of geographically favorable land with respect to soil quality or topography to facilitate drainage or areas that have higher levels of infrastructure can upwardly bias estimates of irrigation's impact, as they are correlated with higher farm productivity. Selection bias due to voluntary take-up can lead to correlations between the farmer's selection probability and the farmer's characteristics, including their geographical location, asset, and political connectedness, among others, which also may be correlated with farm productivity.

Estimation of the effects of irrigation may also include nonrandom measurement error due to survey design choices in production, land, labor, and input modules. An emerging literature estimates land measurement bias due to self-reported errors in land size (e.g., Carletto et al. 2013, Dillon et al. 2019). Production estimates using longer recall periods, self-reported production statistics, production diaries, or crop cuts could also introduce bias in yield estimates (Beegle et al. 2012, Desiere & Jolliffe 2018). Labor measures may be biased if gender affects the classification of women's work (Bardasi et al. 2011) or the data collection method relies on self-reported labor data over longer recall periods (Arthi et al. 2018).

Apart from the direct estimation of irrigation's impact on farmers and their households, we also highlight econometric challenges in the measurement of spillover effects on input markets, food prices, and labor markets. As irrigation can benefit larger populations than just beneficiaries with access to irrigation, it may be difficult to establish a counterfactual comparison. If comparison households who would be compared to beneficiary households also have access to more developed input markets, lower food prices, or a more integrated farm labor market, estimates of the effect of irrigation could be underestimated as the spillover to these nonbeneficiary households would not be considered. As Smith & Todd (2005) have illustrated in the propensity score matching literature, comparison of beneficiaries and nonbeneficiaries in differing markets limits their comparability and biases impact estimates.

4. THE IMPACTS OF DAMS ON HUMAN WELFARE

In this section, we describe some of the existing evidence for the wide-ranging impacts of dams, starting with direct impacts of irrigation dams on yields and agricultural productivity, and on their temporal variability, which is a unique potential benefit offered by irrigation. Our review only includes studies that have used observational data to estimate impacts, ruling out studies based on simulation or modeling that inherently require additional assumptions.

4.1. Downstream Impacts on Agricultural Productivity and Income

Given the widespread water stress experienced by farmers in many developing countries, it would hardly be surprising to find that access to irrigation is associated with positive impacts on production and income. From a policy perspective, the crucial question is not whether impacts are positive, but whether they are large enough to justify the high costs of centralized irrigation infrastructure. In this context, the possibility that selection bias leads to overestimation of irrigation impact is motivated by concerns that farmers' characteristics may be correlated with their access to irrigation or site selection may be correlated with farmers' characteristics. Overall, empirical estimates of the impacts of centralized irrigation on agricultural productivity, income, and poverty that make use of observational data are rather few.

For example, Gebregziabher et al. (2009) use propensity score matching techniques to estimate the impacts of irrigation on about 300 farmers in Tigray, Ethiopia. Overall, they find that irrigation doubles farm income. Limiting the sample to surface irrigation by microdams yields similarly sized, but statistically imprecise, results. Jain et al. (2018) compare the impacts of different kinds of irrigation sources on village-level cropping intensity (specifically, the extent of dry season cultivation) in India using remotely sensed data. They find that surface irrigation performs similarly to irrigation from shallow open wells but poorly in comparison to irrigation from deeper groundwater tubewells, even when comparisons are restricted to villages in the same state or district.

Techniques like those used by studies like these can be effective in addressing selection on observables, but their results remain vulnerable to bias resulting from selection on unobservables. The first analysis to have rigorously addressed this issue was offered by Duflo & Pande (2007), and their approach has since been implemented in most other studies of the impacts of dams.

Duflo & Pande (2007) apply an instrumental variables approach that exploits geographical variation in the suitability of dam construction within Indian states. The variation stems from engineering considerations that imply that locations where rivers have a relatively gentle but nonzero slope are best suited for dams. Using this approach, they find that districts downstream from a dam experience an increase in irrigated areas (by about 30%), cropping intensity, yields (20%), and production (especially of water-intensive crops). As we discuss below, however, they also find stronger negative impacts in the district in which the dam is constructed.

Several other studies have followed Duflo & Pande's (2007) in using similar empirical approaches to estimate the impacts of dams in Africa (Strobl & Strobl 2011, Blanc & Strobl 2014) and globally (Zaveri et al. 2016). Both Strobl & Strobl (2011) and Zaveri et al. (2016) make use of remotely sensed gridded data on net primary productivity (NPP), a measure of vegetative growth. The ability to use gridded data has the advantage of more precisely identifying areas downstream from dams than when the analysis is conducted with data defined at the level of administrative units. Strobl & Strobl (2011) find that upstream dams increase NPP by about 20%, similar to what Duflo & Pande (2007) found. Zaveri et al. (2016) estimate a 7% increase in NPP downstream of a dam. Blanc & Strobl (2014) also compare impacts on productivity from large and small dams in South Africa. They estimate an internal rate of return of 8% given higher construction costs relative to smaller dams. Blanc & Strobl (2014) note that isolating effects between small and large dams may understate the returns to large dams if multiple smaller dams are built in similar large watershed basins, as the multiple smaller dams would incur coordination costs for similar water control within the watershed.

Although not placed in a developing country, another analysis that examines the impacts of access to irrigation water from dams built during the twentieth century in the western United States is offered by Hansen et al. (2009). They use a difference-in-difference approach to compare changes in agricultural outcomes in counties that can access water from a dam before and after its construction in relation to counties with similar agro-climatic endowments and find that access to irrigation water from dams increases the yields of several important crops.

4.2. Downstream Impacts on the Variability of Production

In addition to increases in mean productivity, the potential of irrigation infrastructure to reduce climatically driven variance in production is widely heralded. Several of the studies mentioned above examine this issue as part of their evaluations of centralized irrigation infrastructure. As discussed above, it is not clear a priori whether irrigation can be expected to deliver this stabilization service. For example, farmers downstream of a dam may shift to crops that are more water intensive or sensitive to moisture deficiencies, potentially offsetting the effects of water availability.

Some of the earliest evidence in this vein is provided by Attwood (2005), who credits the construction of large-scale canal irrigation systems for much of the stabilization of grain prices and famine prevention in arid parts of western India during the nineteenth and early twentieth centuries. Jain et al. (2018) find that in comparison to villages irrigated with bore wells, cropping intensity is more variable and more dependent on local precipitation in villages irrigated by canals (or open wells tapping shallow aquifers).

In the western United States, Hansen et al. (2009) find that even though access to irrigation does not seem to have significant impacts in normal years (perhaps because crops grown in these arid areas do not require irrigation when rainfall is adequate), during drought years more area is cropped with wheat, and harvests are less likely to fail in counties served by dams. During years of both deficient and excessive precipitation, the yields of several crops also benefit comparatively.

All three estimates of the impacts of irrigation dams that make use of geographical instrumental variables, mentioned above, also examine whether agricultural production becomes less dependent on local rainfall downstream of a dam. Duflo & Pande (2007) find evidence in support of this hypothesis in India: Agricultural production is correlated with local rainfall, but the correlation declines after a dam is constructed upstream.

Zaveri et al. (2016) find similar evidence in a global analysis of NPP: They find that NPP is positively correlated with local rainfall, but less so downstream from a dam. In contrast, Strobl & Strobl (2011) find no comparable evidence in Africa: NPP is generally correlated with rainfall, but there is no evidence this relationship is muted downstream from a dam. One potential reason for the difference in estimates is that Zaveri et al. (2016) limit the analysis to dams of greater storage capacity than do Strobl & Strobl (2011). It is worth noting that NPP is defined in per-unit-area terms and is therefore comparable to agricultural yields, rather than to total production, the product of cultivated area, and yields (per unit area). Impacts on NPP therefore only capture responses on the intensive margin and neglect the potential shrinking of cultivated areas in response to drought observed in other studies (e.g., Auffhammer et al. 2006). Zaveri et al. (2016) also examine changes in cultivated land during droughts and find that it increases in response to same-year rainfall as well as in response to droughts occurring over the past decade, but only in developing countries. They interpret the latter effect as reflecting adaptation to recurrent droughts through the expansion of cropland in order to satisfy minimum food demands (related to the Borlaug hypothesis). After dam construction, they find this response was reduced downstream, consistent with the reduced sensitivity of yields (proxied by NPP) to drought.

Strobl & Strobl (2011) examine another type of climatic variability that can affect its downstream impacts: precipitation in the location of the dam itself. This is an important source of potential variability in a dam's benefits that is usually neglected in other studies. They find that productivity increases downstream of a dam only when there is no drought in the dam's location, presumably because drought may affect water levels in the dam's reservoirs or because water is first allocated to domestic needs during droughts.

None of these studies, however, estimate the net overall impact on variability, i.e., whether the interannual variance of production declines with access to irrigation, as do Jain et al. (2018). Because, as described above, sources of variability in water supply may not be limited to precipitation at the observed district itself, causal estimates of these summary impacts on variability may be worth including in future studies.

4.3. Downstream Impacts on Input Use and Costs

To fully realize the benefit of water control on agricultural yields for farmers, it is assumed that complementary inputs and output markets are required. The integration of input and output markets affects both the cost and revenue margins of producers. While a large literature estimates unit costs of large-scale irrigation investments from the planner's perspective (World Bank 2007), a much smaller literature estimates the impact of input costs on agricultural productivity or how the integration of output markets may reduce farmers' harvest transport costs and access to competitive commodity prices. Ultimately, how input markets adjust to irrigation investments depends on factors such as transportation cost, national trade policy for agricultural inputs, and farmer crop choice.

Goldman & Squire (1982) estimate the impact of relative factor prices for labor and capital on multiple cropping farm income. They find that in the Muda Irrigation Scheme in India, access to irrigation and hybrid seeds increased agricultural wage labor demand. Accounting for these income changes between farmers and landless laborers, they conclude that large-scale irrigation actually reduced inequality due to rising labor input costs for farmers.

Duflo & Pande (2007) do not find an impact on fertilizer use in India among farmers who have access to dam irrigation. In a cross-country descriptive study, Sheahan & Barrett (2017) find variability in the correlations of fertilizer use with irrigation among six African countries with nationally representative survey data. Despite the potential for increased returns from an agronomic perspective, complementary investments to irrigation are not always undertaken by farmers, but the agronomic hypothesis of higher yields with complementary investment in inputs is not validated in the few studies that estimate irrigation's effect on fertilizer use or other inputs.

4.4. Downstream Impacts on Poverty

Several studies go beyond estimating the agricultural production impacts of dam irrigation and also explore downstream (in the economic sense) impacts on poverty. The implicit assumption is that all such impacts are mostly driven by an agricultural production channel.[8]

Duflo & Pande (2007) find that after dam construction, per-capita expenditure and agricultural wages increase downstream, whereas the poverty headcount and poverty gap (amount of income needed to bring the consumption of the poor to the poverty line) decline. The estimation strategy allows these estimates to be causally interpretable. Moreover, the interannual correlation of these welfare measures with local precipitation declines as well, similar to agricultural production.

Dillon (2011) finds effects of large-scale irrigation in northern Mali of a full standard deviation on consumption per capita, but consumption per capita is relatively low in northern Mali. In terms of poverty reduction for an average household, access to large-scale irrigation reduces poverty by

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[8] While some of the papers discuss the conditions under which agricultural gains do indeed translate into improvements in consumption or poverty, the discussion is not, in its essence, unique to the case of irrigation, but applies to other types of yield enhancing technologies, and therefore lies outside the scope of this review. We therefore confine ourselves to describing the range of observed impacts and only discuss aspects of this issue that are specific to the case of centralized irrigation.

12 percentage points. Sellamuttu et al. (2014) present observational evidence that surface irrigation reduces both chronic and transient poverty, which likely reflects the aforementioned impacts on both the mean level and variability of agricultural production.

Studies of other welfare measures, however, find contrasting evidence about the stabilizing impact of dams on downstream sensitivity to precipitation. Sarsons (2015) follows Duflo & Pande (2007) in showing that agricultural production and wages in India become less sensitive to rainfall shocks downstream of a dam, but she also shows that the probability of religious riots does not. Sigman & Olmstead (2015) conduct a global analysis of the impacts of irrigation dams on economic activity, proxied by nighttime lights, which account for endogenous dam placement through an instrumental variables approach similar to that of Duflo & Pande (2007). They find that while economic activity is reduced by droughts, dams appear to worsen this effect downstream. They attribute this effect to a shift to more water-intensive production technologies, as corroborated by Hornbeck & Keskin (2014) in the United States.

4.5. Downstream Impacts on Flooding

River floods present one of the most harmful types of natural disasters, in terms of both lost life and economic damage. Control of river flow can help protect agricultural production, infrastructure, public health, and human life from these potentially disastrous impacts. Despite its importance, there are surprisingly few credibly causal estimates of the impacts of flooding on economic development, even though the available evidence suggests these impacts can be far reaching, leading to migration (Gray & Mueller 2012, Hornbeck & Naidu 2014, Chen et al. 2017) and wage losses (Mueller & Quisumbing 2011).

Jongman et al. (2015) show that economic vulnerability to flood events varies widely across countries and over time, but it is unclear how much of this variation can be attributed to flood control infrastructure such as dams.

Our review did not yield any causal estimates of the specific impacts that dams may have on human welfare through the control of floods, although it is of course possible that some of the overall impacts on welfare downstream from a dam are mediated by the reduction of flood risk.

Several of the many studies that use panel data to estimate the impacts of weather shock at the country or subcountry level find that extreme precipitation, and not only droughts, harms productivity or growth (e.g., Brown et al. 2013). These impacts may potentially operate through local flooding but probably do not represent the impacts of major river flooding originating upstream from the observed impact. In any case, the few existing studies that estimate the causal impacts of dams on the weather-production relationship tend to focus on whether dams mitigate the impact of drought, and less so on extreme precipitation.

4.6. Near-Dam Impacts of Inundation and Displacement

There are various reasons to expect dam construction to have negative impacts in the areas in the vicinity and upstream from a dam. One of the most extreme consequences of dam construction is likely to be the displacement of populations and the destruction of human-made and natural capital that inhabit the area that is flooded in the process. Globally, dams are estimated to have displaced 40 to 80 million people during the last half-century (World Comm. Dams 2000). But there is also evidence that even land in the vicinity that is not inundated can suffer a loss of quality because of increased salinization and water logging. Moreover, water use in areas upstream of the reservoir might be restricted to enhance accumulation (World Comm. Dams 2000).

Duflo & Pande's (2007) analysis also assesses impacts in districts in which dams are located. In contrast to the positive impacts found downstream, they find evidence of increased poverty and variability of agricultural production in these districts. Similarly, Strobl & Strobl (2011) find that agricultural productivity near the dam becomes more susceptible to rainfall deficiency.

Zhang (2018) conducts a more geographically precise analysis of the impacts of inundation in the case of the Three Gorges Dam in China, a giant (the world's largest) and controversial hydroelectric power plant project that involuntarily displaced 1–2 million people. Using microdata and a difference-in-difference strategy to compare counties differing in the degree of inundation before and after inundation, she finds that inundation led to sharp declines in employment in manufacturing and capital intensive sectors, with some compensating employment in agriculture. Most of the displaced moved within the counties that were affected by flooding, but labor market impacts were more severe for those who did not move.

4.7. Electrification

Hydroelectric dams,[9] which generate 16.4% of the world's electricity and 71% of all renewable electricity (World Energy Counc. 2016), often provide population-wide benefits via electrification and an expansion of power grid capacity. Benefits from electrification expand the impact of large-scale water control investments beyond the agricultural sector. Increased efficiencies in firms due to electrification potentially increase firm productivity, inducing firm growth, higher wages, and employment expansion. Short-run fixed inputs also increase economic growth in electrified areas, generating additional benefits from technical change (Morrison & Schwartz 1996).[10]

Lipscomb et al. (2013) estimate the effects of hydropower expansion in Brazil from 1960–2000 using a fixed effects and instrumental variables strategy, developing an instrument based on geographic cost variables, similar to Duflo & Pande (2007) and Strobl & Strobl (2011), and on plausibly exogenous budgetary allocations. Their estimates address the econometric challenges of identification and estimation of the direct and indirect benefits of electrification using a hedonic valuation of land values. Land value estimates from the electrification of Brazil over this period suggest an 18.4% return above the cost of provision, which has averaged 10–12% guaranteed returns to electric companies.

4.8. Health Effects

Dams have differential impacts on households, depending on whether they are upstream or downstream. Water control advantages agricultural production, increasing income and food availability, but it also increases the risk of water-related infectious disease (for example, schistosomiasis and

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[9] Countries in Asia have the highest hydroelectric power potential from unutilized potential sites with China already accounting for 26% of hydroelectric global capacity in 2015 relative to the United States (8.4% of global capacity), Brazil (7.6% of global capacity), and Canada (6.5% of global capacity) (World Energy Counc. 2016).

[10] A large literature notes the benefits of electrification without specifically linking the source of electrification to hydropower. World Bank (2008) notes the multitude of impacts from rural electrification, including labor market and information effects from television and other information and communication technologies. Khandker et al. (2013) estimate gains from electrification in Vietnam to reach 28% income gains and that these gains occur primarily for richer rather than poorer households. Gains in schooling accrued for both boys and girls from improved attendance (6.3% for boys and 9% for girls) as well as increases in the years of schooling (0.13 years for boys and 0.9 years for girls). Dinkelman (2011) estimates the effects of rural electrification in South Africa on employment. Female employment increases over a 5-year period but has distributional effects between men and women. While both men and women increase hours of work in response to electrification, male earnings increase, while female wages are depressed. Although the literature is generally optimistic about the overall benefits of electrification and even notes that electrification may reduce domestic labor responsibilities for women, the gender-specific distributional effects may create differences in welfare impacts.

malaria) as well as potential community sanitation problems. Increased storage of water at the ground level increases vector-borne illnesses, whereas drainage and poor sanitation increase the likelihood of contaminated potable water. For households that do not reside in irrigated catchment areas, reduced water availability further downstream may reduce vector-borne illness incidence, but it can exacerbate poverty, as further downstream farmers may have reduced agricultural production potential.

When water sources for irrigation contain high levels of human or industrial waste, cadmium and lead that are sequestered in soils are introduced into the food supply. Human consumption of heavy metal–contaminated foods reduces immune system response, impairs intrauterine growth, increases malnutrition, and increases the prevalence of upper gastrointestinal cancer (Iyengar & Nair 2000, Türkdoğan et al. 2003). Animal consumption of contaminated water, particularly when cattle consume irrigated wastewater or ingest fodder from irrigated areas that have been contaminated, introduces heavy metals into the human food chain via milk production.

The World Health Organization (Fewtrell & Bartram 2001, Keiser et al. 2005) estimates the epidemiological risk of irrigated agriculture on malaria burden at a national and regional level. The assumed pathway of higher malaria incidence related to increased hydrological investments is not well substantiated. None of the studies reviewed in Keiser et al. (2005) found increased prevalence of malaria, which was corroborated by Ijumba & Lindsay (2001). In the case of schistosomiasis, ambiguous health effects across projects may be related to engineering differences and water management practices. McCartney et al. (2005) report that projects such as the Mushandike irrigation scheme in Zimbabwe were intentionally designed to address health concerns by locating the project away from villages, using concrete-lined canals, and ensuring water flow velocities that would dislodge snails. Water management practices in the project ensured quick drainage, routine cleaning of canals, and drying of canals that resulted in lower infection rates over a 10-year period. Duflo & Pande (2007), in their analysis of the impact of dams in India, do not find evidence that dams increase the prevalence of malaria.

In South Africa, Mettetal (2019) uses a fixed effects and instrumental variables strategy to estimate a net 10–20% increase in the risk of infant mortality. Two possible channels are identified for this overall effect, including increases in water pollution and reduced water availability. Chakravarty (2011) estimates the aggregate risk of infant mortality conditional on residence just downstream or further downstream from a dam in 17 African countries. Children born in beneficiary households downstream have a reduced infant mortality rate of 6.19–6.96%. Further downstream, the risk of infant mortality rises by 2.18–2.36%. Increased morbidity is also significantly associated with large-scale irrigated areas, such as the Musi River in India (Srinivasan & Reddy 2009).

4.9. Net Effect on Welfare

The previous sections have outlined the geographically heterogeneous impacts that dams can have on diverse dimensions of human and environmental welfare. We have seen that rather few papers provide credible estimates of any of these impacts. An integral analysis that can help assess the overall net effect of dams, which is the ultimate outcome of interest from a public policy point of view, would need to estimate impacts across all of these sectors and geographies, making it even more difficult and therefore quite rare.

Even if it were possible to determine that a dam's net impact on average income or welfare is positive, the strikingly uneven distribution of dams' positive and negative impacts across geographies is as important to consider, unless one assumes that institutions exist that redistribute gains equitably to compensate losers.

Duflo & Pande (2007) take their findings of the negative upstream and positive downstream impacts as an indication of the redistributive failure of state institutions. Bao (2012) directly examines the extent to which government transfers attempt to compensate losers. She analyzes the impacts of large dams in China, using a difference-in-difference approach that compares administrative areas located near to and away from the dam before, during, and after construction. She finds that upstream counties experience a decline in local government fiscal revenue, whereas the area in which the dam is located experiences an increase. However, she shows that transfers from the central government to affected upstream counties are able to mitigate some of the losses and redistribute the impacts to be more equitable.

The distributional consequences of dam creation can also extend across international borders. In such contexts, the relative weakness of international versus national institutions makes redistribution less likely. Olmstead & Sigman (2015) find that countries are more likely to construct dams on internationally shared rivers upstream of national borders, suggesting they do not internalize all of the downstream impacts, especially where international water treaties are absent.

5. DAMS AND SUSTAINABLE DEVELOPMENT

Increased attention to sustainability considerations is gradually reshaping the discussion of the merit of hydrological infrastructure, giving increased attention to the long-term performance of dams and their environmental viability. From an environmental perspective, dams offer a complex package of benefits and costs. Hydroelectric dams are one of the main global sources of renewable energy and, as such, can play an important role in reducing the carbon intensity of energy supply. However, dams are also thought to have detrimental local and downstream ecological impacts.

Another threat to the long-term viability of dam construction stems from limits on surface water flows. Hydrological infrastructure is already diverting and storing large fractions of global natural surface flows, raising questions about the potential for expansion in surface irrigation. The increasing scarcity of surface flows, and the possibility that climate change may substantially alter them, will force surface irrigation systems to become more efficient and wasteful than they currently are.

5.1. Irrigation Efficiency

Current surface irrigation infrastructure is widely thought to be inefficient and inequitable, especially in developing countries where effective distribution and pricing systems are often absent in canal systems. With rising water scarcity, improved efficiency is becoming a growing priority for future projects. More efficient water usage can potentially expand the area served by dams and allow more irrigation water to reach downstream users.

Burt et al. (1997) define the ratio of effective water to the amount of consumptive water use as irrigation efficiency at the plot level. Consumptive water use is defined as the amount of water withdrawn from the water source and used for agricultural purposes. Plot-level irrigation inefficiency in canal systems primarily results from high water application for a given yield. At the level of an irrigation basin, irrigation efficiency can be defined as the consumptive water use in the amount of water applied for agricultural purposes minus the return flow of water via alternative uses downstream and runoff within the basin. Runoffs could be used for alternative purposes downstream or could recharge water sources through water recycling, but inefficiencies related to high water use for a given yield are of major concern, as much water runoff is not used for productive purposes.

Improvements in the technical efficiency of water delivery and irrigation practices may not be sufficient to improve water use efficiency at the system level, i.e., reduce demand by current users and expand the area served by dams to additional users. While empirical evidence on the matter is scarce in developing countries, there are both theoretical arguments and empirical evidence from other contexts to suggest that dynamic substitution effects and behavioral factors may in fact lead to the opposite outcomes (see Grafton et al. 2018 for a review).

For example, Pfeiffer & Lin (2014) find that increased irrigation efficiency in western Kansas failed to reduce overall water use, because farmers shifted crop patterns in response to lower water costs and expanded irrigated areas. On existing fields, farmers actually increased the overall amounts of water used. Grafton & Wheeler (2018) find that (subsidies for) improved irrigation efficiency in the Murray Darling Basin in Australia failed to recover water flows to the environment, with much of the gain from increased efficiency accruing to private irrigators. Xie & Zilberman (2018) model trade-offs between improving water storage capacity and water use efficiency, exploring conditions under which there are complementarities between storage and efficiency. In earlier work on irrigation efficiency, it is presumed that increased irrigation efficiency will reduce the demand for water. Xie & Zilberman's (2018) theoretical work finds that marginal benefit of water storage capacity can be disaggregated into a marginal water benefit pathway and a full dam probability pathway. Irrigation efficiency can increase the demand for water storage if a dam's capacity constraint binds, which could increase or decrease the demand for water depending on the marginal water benefit that can vary across dam sites. Demand for water increases when water demand is elastic. Higher efficiency can also increase the demand for storing more water through dam capacity investments.

Even though the insights offered by Pfeiffer & Lin (2014), Grafton & Wheeler (2018), and Xie & Zilberman (2018), among others, are derived from high-income contexts, there is little reason to expect them to be less relevant in a developing country context. In fact, the relative absence of effective regulation or pricing of water withdrawals in developing countries (Tsur & Dinar 1997, Johnson et al. 2003) may only serve to exacerbate these phenomena. Relevant evidence is therefore important to produce in a developing country context.

Another important avenue for future research is related to the effects of pricing irrigation water. Efficiency gains through correct pricing of water are attractive in principle but may be constrained by behavioral and institutional factors. Tsur & Dinar (1997) review alternative irrigation pricing mechanisms, including volumetric, output, input, tiered, and two-part tariff methods, demonstrating that each theoretical model achieves efficiency but varies in terms of information requirements and administrative costs.

Several recent surface irrigation projects in developing countries make use of large-scale efficient piping and water delivery systems, including drip irrigation, to maximize the efficient use of scarce water.[11] Such projects have the potential to reinvent centralized surface irrigation systems in an age of water scarcity. Given their high costs and the strong implicit assumptions they make about the ability of smallholder farmers to properly employ efficient irrigation technologies, evaluations of the performance of such projects are also an important priority for future research.

5.2. Collective Action for Water Control Management

Independent of dam capacity, collective action for water control management is critical for irrigation construction, canal maintenance, and drainage throughout an irrigation system. Attwood (2005) discusses irrigation infrastructure constructed in western India in the nineteenth and early twentieth century. Even at that early period of irrigation development, some of the chronic problems of canal irrigation were already apparent, including the difficulty of recovering large

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[11] The most well-known project is located in Karnataka, India. See **http://www.newindianexpress.com/states/karnataka/2018/jan/28/asias-largest-drip-irrigation-project-ramthal-to-become-operational-in-karnataka-today-1764446.html**.

construction costs by the state, poor administration, and inefficient management of uncertain flows. Cost recovery was made particularly challenging by initially low demand by farmers cultivating grain crops, which only required irrigation during droughts and were not remunerative enough during normal years to justify the costs of irrigation. Bundling of cash crop cultivation (sugarcane) with cereals helped increase demand.

Early problems of collective action in irrigated schemes were also well noted in other contexts distinct from the Green Revolution, particularly when land rights were not well established. Coman (1911) and Ostrom (2011) describe the unsettled problems of irrigation in the American West during the nineteenth and twentieth centuries. In an effort to formalize water rights in legislation, legislators relied on English common law doctrines of riparian water rights, namely, that those with property rights bordering water resources have first-use rights. In water-scarce areas, riparian rights may not lead to the optimal distribution of water. An alternative water rights system based on use history may be more efficient (Blomquist & Ostrom 2008).

Although the literature does document collective action failures in irrigated production schemes, decentralization of water management in irrigation systems has been successful in some contexts (Meinzen-Dick et al. 2002, Ostrom 2011, Chhatre & Agrawal 2008). Therefore, Ostrom argues that the existence of a collective action problem does not inherently imply the government is the best actor to manage complex production systems through the direct management or enforcement of rules or rights. A large literature also documents the failure of government intervention in collective irrigation schemes (Chambers 1988, Meinzen-Dick 2007, Cox & Ross 2011, Suhardiman & Giordano 2014, Harrison 2018) due to conflicting interests within irrigation bureaucracies and increased costs associated with government bureaucracies. In the context of dams, government management or private sector management of the dam itself could not be turned over to community organizations, but many downstream water management and maintenance decisions, particularly for agricultural production, involve collective action.

Despite failures of government intervention to resolve collective action problems, the determinants of collective action success are not consistent across irrigated schemes. Poteete et al. (2010) find that group size or the potential payoff to actors is not predictive of cooperation because ecological factors, the distribution of the types of actors in the collective action problem, and the governance system are all constraints. Increasing farmer participation through decentralization is also not a panacea (Senanayake et al. 2015, Nagrah et al. 2016), depending on whether the type of collective action problem with the irrigated scheme is considered. Decentralization of irrigation management to water users associations may reduce government expenditure, but hydrological problems often require external expertise, and prioritizing maintenance and managing institutions to set and collect water fees and provide extension advice are not straightforward.

The likelihood of either government or community institutions to resolve collective action problems to promote community welfare also depends on gender social norms. Van Koppen & Hussain (2007) provide a review of gender and irrigation issues, noting that gender-sensitive irrigation institutions need to consider property rights, differences in farming systems between men and women, and the need to consider the distributional welfare of water within the community for both farming and domestic uses. The initial distribution of property rights within irrigated areas and use rights in the larger water system are critical to the gender welfare distribution within large-scale irrigation investments (Meinzen-Dick et al. 1997).

5.3. Environmental Consequences and Opportunities

Dams can have widespread environmental impacts that constrain agricultural productivity and mitigate potential poverty-reducing benefits. A large literature documents environmental impacts through flooding of natural habitats, deterioration of water quality, and health impacts that we reviewed previously (Ongley 1996, FAO 1997, World Comm. Dams 2000, Ledec & Quintero 2003, UNESCO 2015, Mateo-Sagasta et al. 2017). We focus on land quality issues in this section related to salinization, silting, flooding, and reservoir sedimentation that can affect agricultural potential and technical efficiency of an irrigated area. We also focus on the pathways in which large-scale hydrological investments may contribute to climate change as well as mitigate potential effects of climate change in water-scarce environments (IPCC 2018).

As irrigated water floods and drains from agricultural plots, soil salinity results from a high concentration of ions that restrict plant growth by reducing water and nutrient uptake and soil aeration. Soil salinization depends not only on the frequency of irrigation that raises the water table, but also initial soil conditions, irrigation water salinity (Hillel 2000), temperature, and evapotranspiration rates (Mateo-Sagasta et al. 2017). Vlek et al. (2010) summarize the literature on soil degradation and irrigation from an agronomic perspective. Hatfield (2015) also describes potential environmental effects within watersheds. Irrigation affects the hydrologic cycle, altering groundwater recharge for alternative uses and users. Effects of changes in groundwater recharge can affect wildlife habitat and wetlands.

Large-scale hydrological investments are also central to climate change adaptation policy (IPCC 2018) and creating a sustainable food supply (Foley et al. 2011). Kurukulasuriya et al. (2006) estimate potential implications of climate change on agricultural productivity using a sample of 11 African countries. They observe that implications of irrigation's potential to address climate change are driven by the magnitude of dryland crop and livestock revenue losses relative to potential revenue increases in areas that have irrigation potential. Rainfall uncertainty potentially affects revenues for both dryland and irrigated areas. The authors estimate that differences between countries and production systems range between $US150 and $US5,000 per hectare in 2000 prices. In comparison, Inocencio et al. (2005) estimate that irrigation investment costs in sub-Saharan Africa range between $US3,600 and $US5,700 per hectare. In low-cost areas, large-scale hydrological investments could be profitable, but the returns are certainly variable across countries.

6. CONCLUSION

Dams represent one of the principal forms of infrastructure investments for economic development. Dams can require large public expenditures and create a spatially and temporally complex structure of benefits and costs to both humans and the environment. It is therefore no wonder that they remain a controversial form of investment. Because irrigation is widely held to hold the key to expanding food production in many parts of the developing world (and protecting it from the threat of climate change), and because groundwater resources are being rapidly depleted in many of these areas, it is unlikely that the relevance of large-scale surface irrigation for development will diminish in the foreseeable future.

The importance of dams in both historical development trajectories and the new sustainable development agenda stands in stark contrast to the scarcity of credible, causally interpretable evidence on their socioeconomic impacts. Such evidence is especially important in the case of centralized irrigation because of the likelihood of endogenous placement. The evidence is especially thin when it comes to nonagricultural impacts, such as those occurring through flood control or through the supply of energy. The multiple pathways through which dams can affect human health and nutrition are also covered by a relatively thin literature, with clear trade-offs between positive income effects from increased agricultural profitability and the negative externalities of sanitation and water quality. In the agricultural context, it is especially important to improve our understanding of the distribution of dam water among users and the efficacy of approaches—incentive-based or technical—that can improve the efficiency of water use. General equilibrium effects on input markets and transportation costs are also areas of research not well covered in this literature.

Research gaps in this literature remain substantial due to the identification challenges associated with selection bias, sampling to capture distributional outcomes, and panel data to estimate longer-term effects, as impacts may not be constant over agricultural seasons, and they change over time. Most causally interpretable evidence to date is based on aggregate data at the level of rather large administrative units and on a single identification strategy originally developed in the seminal work of Duflo & Pande (2007). Additional empirical approaches and the use of microdata could help broaden the evidence base and deepen our understanding of the impacts and the channels through which they occur. In addition, replication of existing approaches in additional geographical and economic contexts would also be valuable given the likely heterogeneity of the relevant impacts.

There remain several important research gaps to address to better inform public and private investment in large-scale irrigation, including those that relate to identifying distributional impacts on profitability and welfare of farmers and food production and on environmental consequences. Filling these research gaps is fundamental to the development of policy responses to water scarcity, rising global temperatures, and poverty.

We are optimistic that continued investments in irrigation and a wider appreciation of the challenges of selection bias in empirical fields such as resource, development, and agricultural economics will provide future opportunities for researchers to contribute to these empirical questions and the formulation of irrigation policy.

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