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Water supply and dams in agriculture

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1 Introduction

Water is crucial for agriculture, but it needs to be allocated and managed effectively to address variability over space and time. The design and management of water infrastructure has traditionally been a role of governments in major societies (Water Technology Net 2016).

Dams and aqueducts have been major sources of the supply of water for agriculture, which accounts for 70 percent of total water use (van der Zaag and Gupta 2008). The role of dams in agriculture has been primarily to address seasonal water variation and to assure the success of multiple cropping (Brown and Lall 2006). Dams are also crucial in reducing the risk of flood and allocating water among seasons and between regions (IEA 2011). Dams supply 86 percent of the renewable energy in the world. However, increased urban water demand and emphasis on environmental amenities have raised concerns about the construction of new dams, and this has exacerbated the challenges of optimal water resource management. This chapter addresses some of the challenges of water infrastructure, mostly in the context of agriculture.

There has been a long, multidisciplinary policy debate about the value and viability of dams. The next section provides background on some of the debate and major issues. Afterwards, we present conceptual modeling on the design and implications of water storage systems. We also discuss farmers' response to dams, followed by an overview of empirical analysis and a conclusion.

2 Background on dams

Dam technology dates back to 1300 BC. There are as many as 50,000 large dams in the world today, compared to about 5,700 in 1950 (Scudder 2012). Dams supply water for the irrigation of 30–40 percent of the 271 million hectares of irrigated lands (FAO 2015, 2017). Irrigated agriculture produces about 40 percent of the food and fiber in the world. On a per-unit land basis, irrigated land produces more than five times the economic value of non-irrigated land (Schoengold and Zilberman 2007). This is reflected in land values, such as in California, where irrigated acreage is worth three times that of non-irrigated acreage (USDA-NASS 2012).

Dams and water projects have contributed significantly to increases in both agricultural productivity and manufacturing. Dams are an economic marvel. Almost all large dams cost a significant portion of a nation's gross domestic product (GDP). For example, the proposed Budhigandaki project in Nepal is estimated to cost more than 5 percent of Nepal's annual GDP.

Dams and water projects were a major engine of growth in the western United States during the twentieth century, as they provided an inexpensive energy source. This led, for instance, to the establishment of the aeronautical industry, which needed significant electricity for aluminum production. In addition, much of the research and engineering introduced in developed countries spread throughout the world as the damming of rivers became a major public investment (Reisner 1993). The World Commission on Dams (WCD 2000) noted that dams have made a net positive contribution to human development, but their use also has some major drawbacks.

The World Wildlife Fund (Kraljevic, Meng, and Schelle 2013) noted the potential "seven sins" of dam construction: (1) the choice of the wrong river on which to build the dam, (2) neglect of downstream flows, (3) neglect of biodiversity, (4) a reliance on bad economics (e.g., underestimated costs and construction delays (Bacon and Besant-Jones 1998; Ansar et al. 2014)), (5) a failure to acquire a *social license* to operate, (6) mishandling risks and unintended impacts, and (7) giving too much weight to policy makers' bias in construction decisions. Furthermore, optimal sites for large dam construction are finite, and reservoirs are losing 1 percent of their total capacity each year due to sedimentation deposit, especially in China and the South Asian countries (McCully 1996).

Most dams reallocate resources from riparian local users to many non-riparian stakeholders, which is often politically controversial, with displacement and resettlement a significant social issue. On average, 13,000 people have been displaced for every large dam (World Bank 1996). About 40 to 80 million people have been displaced by dams worldwide, and the lifestyle of the remaining populations have been altered, sometimes negatively (Attwood 2005). Major studies have documented flaws in the design and management of dams, including underestimation of the associated environmental costs (Stone 2011), improper sedimentation management (Poudel 2010), greenhouse gas emissions (Rudd et al. 1993; Louis et al. 2000; Tremblay, Lambert, and Gagnon 2004; Barros et al. 2011), overestimation of energy production (WCD 2000), and economic inefficiencies (Duflo and Pande 2007; Ansar et al. 2014).

Many of the criticisms of dams have singled out large dams, and there has been a lively debate on whether large dams are desirable. Large reservoirs are often correlated with increased economy of scale in terms of both benefits and costs. Large reservoirs support many farmers, attract industries to the region, and support knowledge sharing among the farmers (Lipton, Litchfield, and Faures 2003). While small dams give little aid in coping with serious droughts, large dams increase the welfare of the population (Attwood 2005).

The evidence in favor of large dams over small dams, however, is inconclusive. Hussain (2007) concluded that there is no systematic pattern of increasing or decreasing poverty associated with the size of irrigation projects. While Blanc and Strobl (2014) found that small dams tend to have a higher internal rate of return, their calculation was limited because it did not factor in both the positive (e.g., hydropower and recreational) and negative (e.g., ecological) impacts of large dams. Dillon (2011) showed that while both small and large irrigation systems have similar impacts on agricultural production, small irrigation systems tend to have higher productivity and income impact per hectare, while large systems have a higher consumption effect because they attract more people and create more non-farm employment opportunities.

One of the main arguments against large dams is the significant amount of greenhouse gas emission they create. Barros et al. (2011) estimated 4 percent of global carbon emissions from inland water could be associated with reservoirs, and Louis et al. (2000) estimated almost

7 percent of all other documented anthropogenic emissions could be attributed to reservoirs. In addition, reservoirs are associated with increased malarial and other mosquito-induced diseases, because they provide a breeding ground for mosquitos (Rudd et al. 1993; Tremblay, Lambert, and Gagnon 2004; Keiser et al. 2005; Giles 2006; Kitchens 2013). Also, a major argument against large dams is that they are too big to solve any urgent energy or irrigation need, and planners are either susceptible to planning fallacies or intentionally deceptive when they push for big projects (Ansar et al. 2014; Flyvbjerg 2005, 2009). Ansar et al. (2014) compute that, on average, large dams take 8.6 years to be fully functional. Rangachari et al. (2000), in their report to the World Commission on Dams (WCD) on large dams in India, commented that in many cases, while costs were underestimated, benefits were consistently overestimated.

After losing some support in the 1980s–mid-1990s, there is again a renewed interest in dams, as indicated by ongoing construction of the mega 900 MW Dahuaqiao Dam in China. With growing demand for food and power, international funding agencies are more open to investing in dams that provide irrigation as well as electricity. Better design and better management of dams are essential to improved outcomes.

3 Economic design modeling implications of dams and water supply systems

The construction of dams requires collective action at both the regional and national levels. Throughout the world, water-user associations are involved in diverting water resources for agriculture, mining, and energy. Generally, smaller dams are funded at the local level, while larger dams are funded at the state or international level. Government is often involved in large water projects meant for flood protection, hydroelectric power, and agricultural production. For example, in the United States, the Tennessee Valley Authority (TVA), created in 1933, is a government-sanctioned initiative investing in hydroelectric dams, navigational canals, and road networks (Kline and Moretti 2014).

Since the 1970s, benefit–cost analysis has become a major economic method used by governments and international organizations to assess the benefit of water projects (Schoengold and Zilberman 2007). Criteria used in the benefit–cost analysis includes the expected net present value of market and non-market benefits. It requires the use of economic surplus measures to assess market benefits as well as non-market valuation techniques (National Research Council [NRC] 2004).

Chakravorty et al. (2009) consider water systems to include several components: a water extraction and divergence source (e.g., a dam), a water conveyance mechanism, and a distribution network that allocates water to farmers. The design of a system may include physical parameters as well as managerial parameters, such as the size of the dam (this affects the expected benefit from hydroelectric power, water storage and irrigation, flood protection, and recreation), the lining of the canals (relates to distributional losses from source to use), and incentives for allocation among water users (principles for water pricing). Social welfare maximization may lead to an optimal design by equating the expected discounted social marginal benefits of key dams and the parameters of their expected discounted social marginal costs. If, however, a water project aimed at providing irrigation water is controlled by a profit-maximizing monopoly, it may under-divert and undersupply water. Furthermore, a lack of attention to the environmental services provided by water at the source may result in excessively large diversions and dams. When the design of water projects ignores or underinvests in conveyance, it results in shorter canals and reduces the benefits derived from the projects (Chakravorty, Hochman, and Zilberman 1995). Similarly, when water trading is disallowed or water is underpriced, this may lead to underinvestment in modern irrigation technologies and reduce the benefits of a project (Schoengold and Zilberman 2007). Thus, the economic calculus that determines the scale of a dam or reservoir must take into account the components of the system associated with the project.

The use of irrigation water provided by dams may change over time due to the availability of new technologies. The emergence of new irrigation technologies that include sprinkler and drip irrigation, as well as the use of weather data, affect water use, crop selection, and the profitability of water projects. Modern irrigation technologies increase water use efficiency, that is, the percentage of applied water used by the crop (Caswell and Zilberman 1986) and the timing of irrigation. The adoption of modern irrigation technologies by farmers tends to increase yield per hectare, and when combined with proper chemical applications, leads to a reduction in both input use and the residue of inputs not utilized by the crops (Caswell, Lichtenberg, and Zilberman 1990). The adoption of modern irrigation technologies is likely to save water if the marginal productivity of effective water is declining significantly with water application (technically, the elasticity of marginal productivity [EMP] is greater than one). However, if EMP is smaller than one, this need not be the case. The empirical evidence generally supports that the adoption of modern technologies can increase water use (Ward and Pulido-Velazquez 2008; Pfeiffer and Lin 2014).

Xie and Zilberman (2016) develop a framework on the optimal size of catchment reservoirs (which capture water in the wet season and release it in the dry season), taking into account the uncertainty of precipitation and climate as well as the social benefits and costs of water use. The optimal size of reservoirs is determined by balancing, at the social margin, the cost of construction, the expected cost from flood damage, and the net benefits from reservoir outflow use. They find that dam size increases as potential damage from floods increases, and as the value of output produced by released water increases, which depends on water allocation institutions (e.g., water rights systems, pricing schemes, and the industrial organization of water supply), and as the distribution of inflow skews rightwards, which can be caused by climate change. Another finding is that the adoption of water conservation technologies is not likely to occur when dams are too small (without sufficient scale to cover the cost of conservation) or excessively large (so there is little gain from marginal water conservation). This feature will make the marginal benefit of dam capacity discontinuous, and it will make the impact of overlooking the potential adoption of irrigation technologies on dam capacity choice ambiguous.

Zhao and Zilberman (1999) suggest that there are increasing returns to scale in the construction of dams. Therefore, in some cases where there is an expected increase in future output demand, large irrigation dams may not be fully utilized for several years after construction. While large dam capacity may expand when there is technological uncertainty and increasing returns to scale in construction, it may contract when certain demands for conservation technology and environmental safeguards increase.

Xie and Zilberman (2018) consider the optimal design of dams used for both reallocating water within seasons and storing water over time. They show that increased storage capacity and conservation technologies are not necessarily substitutes. The introduction of water-conserving technologies may actually increase the optimal size of dams when the marginal productivity of water is slowly decelerating (EMP < 1) or when it does so quickly, but the rate of change is small (EMP > 1 and second-order EMP < 2).

Other important theoretical works on storage capacity for agricultural water use include, but are not limited to, Fisher and Rubio (1997) and Truong (2012). Fisher and Rubio (1997) investigate the optimal real-time renovation of storage capacities that manage annual variations in water supply. They show long-run storage capacity is positively correlated with variance in water supply, which can be increased by climate change if the marginal benefit of water release is convex. Truong (2012) builds a competitive storage model to investigate the impact of reducing storage capacities that manage seasonal and annual variations in water supply on the irrigation sector. Results show that capacity reduction will increase the share of dam capacity utilized, on average, and that the value of the irrigation sector will decrease, while the impact on the average water price is ambiguous.

Most of the economic literature on optimal dam size and water supply management takes a microeconomic perspective. However, given the scale of dams and their importance in the overall economy, Kline and Moretti (2014) suggest using general equilibrium, structural, multi-sector models of the economy so that some of the dynamic macroeconomic implications of dams can be captured by growth theory models. One example is given in Hornbeck and Keskin (2015), who apply a two-sector model of economic growth for analyzing the impact of a large aquifer. Firms use technology $f(A, L, K, T)$, where A is the productivity parameter; L is labor input; K is capital input; T is total land; and w, r, and q are the prices of labor, capital, and land, respectively. The farmer maximizes profit $\Pi = f(A, L, K, T) - wL - rK - qT$ with the appropriate choice of L, K, and T, which are all functions of the reservoir. Assuming the normalized output price of 1, the presence of a reservoir R is assumed to enhance the productivity of industry A (one can think of agro-based industries). Optimal values of L and T are functions of wages and rental land price, whereas optimal K is a function of wages, interest rate on capital, and rental land price. Wages and rental land price are also functions of the reservoir, as it attracts industries and individuals to migrate near the reservoir. This increases economic activities and labor productivity. With this model, profitability increases with the size of the reservoir through its impact on all inputs of production:

$$\frac{d\Pi}{dR} = \frac{\partial f}{\partial A}\frac{\partial A}{\partial R} + \frac{\partial w}{\partial R}\left\{\left[\frac{\partial L^{\star}}{\partial w}\left(\frac{\partial f}{\partial L} - w\right) - L^{\star}\right] + \left[\frac{\partial K^{\star}}{\partial w}\left(\frac{\partial f}{\partial K} - r\right)\right] + \left[\frac{\partial T^{\star}}{\partial w}\left(\frac{\partial f}{\partial T} - q\right)\right]\right\}$$
$$+ \frac{\partial q}{\partial R}\left\{\left[\frac{\partial L^{\star}}{\partial q}\left(\frac{\partial f}{\partial L} - w\right)\right] + \left[\frac{\partial K^{\star}}{\partial q}\left(\frac{\partial f}{\partial K} - r\right)\right] + \left[\frac{\partial T^{\star}}{\partial q}\left(\frac{\partial f}{\partial T} - q\right) - T^{\star}\right]\right\}$$

When firms in a country behave like a price taker in the world market, then $\frac{\partial f}{\partial L} = w,\ \frac{\partial f}{\partial K} = r$ and $\frac{\partial f}{\partial T} = q$. This leads to $\frac{d\Pi}{dR} = \frac{\partial f}{\partial A}\frac{\partial A}{\partial R} - \frac{\partial w}{\partial R}L^{\star} - \frac{\partial q}{\partial R}T^{\star}$. Hence, firms, and by extension the aggregate industrial sector, continue to increase profit with reservoir construction as long as the productivity effect exceeds the increase in cost due to the labor impact and the increased value of land. The analysis suggests that a country with both lax labor laws that restrain wages and large amounts of fallow land may continue to build dams profitably, whereas a country with severely limited land endowments and high wages may not be inclined to build more dams.

4 Farmers' response to dams

The socioeconomic status of farmers living in the catchment areas of dams is likely to be heterogeneous, as will their response to dam construction. Baboo (1991), for example, noted that when the construction of Hirakud Dam began in Odyssa, India, wealthy and well-educated farmers migrated to cities, whereas poor farmers remained in designated colonies nearby. Kline and Moretti (2014) also noted that in the United States relatively poorer people lived near the reservoirs built by the TVA because those lands were cheaper due to environmental risks. However, impact evaluation papers (Duflo and Pande 2007; Blanc and Strobl 2014) tend to give light treatment to migration issues in catchment areas. Xabadia, Goetz, and Zilberman (2004) noted that in the absence of corrective water pricing, policies to address heterogeneity in land quality and suboptimal water use behavior, such as the delayed adoption of modern technologies, will be observed among farmers.

Dams also affect a farmer's risk exposure through decreased variance in production, thus affecting a farmer's expected income, *ceteris paribus*. Reduced risk may decrease the urgency for adopting risk-mitigating measures, including new technologies. Conversely, stability in production may increase predictability regarding yield and provide an incentive to invest in productive technology. Farmers' adoption of improved seeds, fertilizers, and efficient water conservation technologies may be affected by their access to stable sources of water. Kovacs et al. (2015) find a substitution of rice with soybean crops when the depth of the aquifer increased in their simulation model. Shakya and Flinn (1985), in their study of the adoption behavior of farmers in Nepal, found that the use of improved seeds was highest in the areas where irrigation facilities existed. However, Koundouri, Nauges, and Tzouvelekas (2006) found that farmers' adoption of new technology increases when their need to hedge against production risk is higher. This was similar to Gerhart's (1975) finding that farmers in Kenya were not adopting hybrid maize as long as they had other means to cope with the risks addressed by these hybrids. Zilberman et al. (2011), in their study of droughts in California, noted that only after the supply of water from reservoirs started to decrease did California farmers begin to respond by increasingly adopting water conservation technologies. Bhaduri and Manna (2014) showed that farm-level storage capacities can encourage the adoption of efficient irrigation technologies. Emerick et al. (2016) showed through a randomized experiment that reduced flood risk tends to improve farmers' income by increasing the intensity of use of complementary inputs like labor and land.

The provision for a stable water source has been shown to affect farmers' behavior in several other analyses of groundwater management. Shah, Zilberman, and Chakravorty (1995) indicate that the adoption of water conserving technologies increases with groundwater depletion, and the optimal management of groundwater requires a tax on reducing the groundwater reservoir level with pumping, which may enhance adoption compared to an open access system. Carey and Zilberman (2002) take the literature further by analyzing a farmer's decision to adopt a new technology under irreversibility and uncertainty. They consider the farmer as an individual facing uncertain prices in the water market and making decisions to invest in water extraction technology. Their quasi-irreversibility setting was distinct from the usual analysis in finance literature where uncertainty was in output price and not in input price. Treating output price as fixed for farmers, they found that anything that stabilizes the price of water is likely to promote the adoption of efficient technologies. Dams therefore promote the use of more efficient water conserving technology insofar as they decrease the variance of the price of water in the market.

Many water systems rely on both ground and surface water. Conceptual optimal control models were used to analyze groundwater management problems (Gisser and Sanchez 1980; Tsur and Graham-Tomasi 1991) while identifying optimal rules for substitution decisions between groundwater and surface water. Many of the studies that consider the conjunctive use of groundwater emphasize the stochasticity of surface water supply and use numerical techniques to find solutions. Knapp and Olson (1995) find that groundwater pumping decreases with surface flows. This implies that farmers will substitute their groundwater use with water available from reservoirs whenever available. Tsur (1990) finds that variance in the surface water supply increases the benefit from the stabilization role of an alternative water source (in his case, groundwater, but as he implies, this could as well be a reservoir). Bredehoeft and Young (1983) also suggest that farmers sometimes should totally disregard the variability in surface water flow and install pumping facilities to extract groundwater resources. If the cost of groundwater pumping and getting water from a reservoir are similar, then farmers benefit from a stable source of water, such as large reservoirs.

5 Impact of dams: empirical evidence

The challenge for empirical analysis based on conceptual models is to deal with issues of dimensionality and multiple correlation. Because dams may be involved with other dynamic investments, it is difficult to separate the impact of dams from other correlated large-scale investments or an agglomeration effect (Kline and Moretti 2014). Murphy, Shleifer, and Vishny (1989) argue that big pushes, such as large dams, transform a society's population, income, and industry by operating through demand externalities. Empirical studies try to find instruments and other methods that attempt to isolate the impact of dams. The verdict in the empirical literature regarding dam construction is mixed. In the past, empirical enquiries generally reported the welfare of people with and without dams (Hussain 2007), often showing a very large difference in the poverty between those irrigated and non-irrigated areas. These results did not have any causal interpretation as the locations of large dams are not randomly selected, and without a robust econometric method that has causal interpretation, evaluating the impacts of dams can be very difficult (Janaiah, Bose, and Agarwal 2000; Ersado 2005).

Duflo and Pande (2007) illustrate the benefit of precisely aiming to disaggregate the impact of dams using a simple fixed effect model, such as $y_{ist} = \beta_0 + \beta_1 D_{ist} + v_s + \mu_t + \varepsilon_{ist}$, where y is the economic variable of interest and D is the number of dams in a district i in state s and year t, which does not have any causal interpretation. They made an influential contribution by suggesting river gradient as an instrumental variable (IV) for dam placement. Their study compares the welfare of two regions upstream and downstream and conducts a robustness check for the migration of mainly the upstream people and the rainfall shocks. They suggest including district-level information directly and using only district and state year fixed effects. If one assumes that the annual variation in dam construction in districts within a state is uncorrelated with other district-specific shocks, the following equation can be written as $y_{ist} = \beta_0 + \beta_1 D_{ist} + \beta_2 D_{ist}^u + v_i + \mu_{st} + \varepsilon_{ist}$, where D_{ist}^u indicates the total number of dams upstream of district i. It will provide a reasonable causal estimate for the impact of dams for a district where the dams are located and for the district that is in the command area of a dam or many dams.

Duflo and Pande (2007) find that dams marginally improve welfare in the command areas, whereas they decrease welfare in the catchment areas. They argue that there is no significant movement of population in catchment districts, undermining claims of endogenous selection by population (as mentioned in Attwood 2005). Districts upstream saw a modest (0.7 percent) increase in irrigated land, whereas districts downstream saw a 1 percent increase in irrigated land. They also found that farmers do not substitute crop production toward more water intensive crops. However, downstream districts had an increased adoption of water-intensive and high-yield variety seeds. The use of fertilizers also increased downstream.

Kitchens (2013) reinforces Duflo and Pande's skepticism about the efficacy of dams, arguing that their estimates included the cumulative effect of other activities associated with dams. Kitchens (2013) documents that reservoirs built by the TVA were likely to have increased the incidence of malaria, and there would have been many more victims of malaria near these dam areas had there been no intervention of DDT or other vector control activities. Kitchens argues that the TVA increased mortality by 3 to 4.4 per 100,000 people and morbidity by 7.1 to 13.9 per 10,000 people. The estimated loss of human health and life due to the TVA reservoirs ranged from US$508 million to US$1.06 billion. The TVA provides an important setting for studying the impacts of dams because of the relatively extensive availability of data. Kline and Moretti

(2014) find that the population increase in TVA counties was significant, while the impact on land price or wages was not.

Subsequent studies have highlighted the positive impacts of dams. For example, Severnini (2014) focuses on a panel of 154 U.S. counties with the hydropower potential of more than 100 megawatts and uses a combination of a synthetic control and event study methods, arguing that the synthetic control method facilitates estimating the county level heterogeneity of the impact. The regression model is:

$$Y_{ct} = \sum_{y} \beta_y D_{ct}^{y} + \alpha_c + \gamma_{rt} + Z_c^{'}\phi_t + X_{ct}^{'}\lambda + \varepsilon_{ct}$$

where Y_{ct} is the outcome of interest; D_{ct}^{y} is the dummy, indicating whether the dam was constructed in the county y years after (or before for negative y) year t; $\alpha_c;\gamma_{rt}$ represents county and region year dummy variables; Z denotes county-specific time invariant variables; and X represents other socioeconomic variables that varied across counties and years. Though the impact differed across counties, on average the population of counties with pre-1950 dams grew by 51 percent within 30 years, whereas there was no such effect for dams built after 1950. His findings of increased population in the catchment area of dams is compatible with the related finding by Hornbeck (2012), who indicated that the main area of adjustment after the American Dust Bowl, which resulted in the massive decline of productivity in the agricultural sector, was population decline. Severnini also investigates the long-term effects of these dams and found that population grew by 120 percent in 60 years. These results were, importantly, independent of dam size. Severnini also calculates the effect of dams for different sectors: agriculture and manufacturing sectors benefited even after 60 years, whereas construction and trade did not, and where aggregate impact on counties was driven by agriculture. Other sectors that benefited significantly included real estate, medical, and legal services. Severnini argues that, based on the evidence, large dams continue to affect the economy for such a long term that they act like an instrument of a big push policy, pushing counties toward a higher sustainable path of development.

Severnini's finding that the manufacturing sector benefited from large dams slightly differs from Kitchens (2014), who clarifies that comparatively lower electricity prices faced by manufacturing firms did not add value to the manufacturing sector. This suggests that firms' location choices at the time were motivated by their desire to benefit from the availability of electricity in a TVA region.

Hansen et al. (2011, 2014) estimate the impact of major storage facilities in the western United States on farming decisions. Dams increase total crop acreage, encourage farmers to choose higher-valued, more water-intensive crops, and increase crop yields, particularly during severe droughts. These findings are consistent with the results in Sarsons (2015) and Takeshima et al. (2016) that, in India and Nigeria, respectively, incomes in agriculture dependent areas that are downstream from irrigation dams are less sensitive to droughts. Hansen, Lowe, and Xu (2014) found little short-term impact on farmland values but found long-term impacts on agricultural development. They show that dams reduce the water available for ecosystem use and increase seasonal volatility in the water supply.

There has been some empirical evidence of failing water project management. For example, Attwood (2005) notes that in India many of the canals are in shambles and asserts that improvement in the canal system could greatly improve irrigation. He blames fiscal irresponsibility and clumsy handling by an expansive bureaucracy in India for the inefficient system and the negative net gain from these large-scale irrigation projects. Citing Rangachari et al. (2000), he asserts that a 10 percent increase in water-use efficiency would create 14 million hectares of additional irrigated land. Even in areas where dams have increased productivity, poverty may be due to an inequitable wealth redistribution system. This fact undermines the external validity of works based on Indian datasets.

In an early analysis, Tsur (1990) argues that many stable sources of water, such as groundwater or reservoirs, lose their value with decreasing rainfall variability. It is also possible that removing from the analysis dams built due to political interference or in areas where rainfall variability is minimal, results obtained are likely to differ from those found by Duflo and Pande (2007).

Lipscomb, Mobarak, and Barham (2013) studied the impact of dams in Brazil, which, while very rich in water resources, is grappling with issues regarding the equitable supply of electricity to its population. They found significant positive effects of dams in Brazil: each 10 percent increase in electrification led to a 3.8 percent increase in the mean housing value. They addressed the endogeneity of dam placement by using a simulation-based prediction of grid-level electricity availability. Furthermore, they also used an Amazon indicator interacted with each decade as their instruments. Their model was as follows:

$$Y_{ct} = \alpha_c^1 + \gamma_t^1 + \beta \hat{E}_{c,t-1} + \varepsilon_{ct}$$

where $E_{c,t-1} = \alpha_c^2 + \gamma_t^2 + \theta Z_{c,t-1} + \eta_{ct}$, where Y was the relevant development outcome, E was the electrification in county c in time t, $\widehat{E}$ was the instrumental variable for E, and Z was the proportion of the grid model forecast to be electrified. Their study found a significant effect of dams on poverty reduction and formal employment generation, which differs from Duflo and Pande due to the focus on hydropower dams rather than irrigation dams.

Strobl and Strobl (2011) showed that in South Africa large dams reduce cropland productivity in their vicinity but augment the impact of small dams. They used 20 years of panel data on land cover, rivers, and productivity and developed the following model:

$$CP_{it} = \alpha + \beta_1 D(L)_{it} + \beta_2 D(S)_{it} + \beta_3 UD(L)_{it} + \beta_4 X_{it} + \varepsilon_{it}$$

where CP is cropland productivity, $D(L)_{it}$ is the number of dams in basin i in year t, $D(S)_{it}$ is the number of small dams in basin i, and $UD(L)_{it}$ is the number of large dams located upstream from district i in year t, and X represents other socioeconomic variables. Endogeneity of dam placement is accounted for by noting that dam placement is largely a function of politics. They specify the following first-stage equation:

$$\begin{aligned} D\ (sz)_{it} = \delta_1 + \sum_{k=2}^{4} \delta_2 \left(RGr(k)_i \star P_{it} \right) + \delta_3 \left(M_i \star P_{it} \right) + \sum_{k=2}^{4} \delta_4 \left(RGr\ (k)_i \star l_t \right) \\ + \delta_5 ERLENGTH_i \left(sz = small \right) \star P_{it} + w_{it} + v_i + \mu_{it} \end{aligned}$$

where $RGr(k)_i$, k = 2,3,4 and indicates the fraction of perennial river in basin i with 1.5–3 percent, 3–6 percent, and a 6–~percent river gradient, $ERLENTH_i$ is the length of the Ephemeral River in basin i, P is policy proxy, M is river basinspecific time invariant characteristics, and $sz \in \{large, small\}$ is the size of the dams.

Dillon (2011) also investigated the impact of the size of irrigation dams on poverty and production. He matched villages in Africa on their observable characteristics and found that small dams caused a larger effect on agricultural production and agricultural income, whereas large dams had a larger effect on consumption per capita.

Ansar et al. (2014) used an outside view method that operates by first identifying a reference class and establishing an empirical distribution for the reference class of the parameter being estimated. They then compared the specific case at hand with the reference class distribution.

They used information on 245 dams (with 26 major dams that are either more than 150 meters tall or can store more than 15 million cubic meters of water or have more than 25 square kilometers of reservoir storage) that were built between 1934 and 2007. Their study showed that Pakistan's Diamer-Bhasha Dam is likely to cost up to US$25.4 billion (in 2008 AD value), rather than the official estimate of about US$12.7 billion. When inflation is factored in, this estimate may exceed US$35.08 billion. Furthermore, instead of the planner's estimated completion date of 2021, this dam is likely to be under construction until 2028.

Kline and Moretti (2014), while evaluating the TVA's long-run effectiveness, compared identical pre-program counties (including those similar to the TVA counties but not chosen) to the TVA counties. Their method was to use the Oaxaca–Blinder regression model for all counties before the TVA started as follows:

$$y_{it} - y_{it-1} = \alpha + \beta X_i + \left(\varepsilon_{it} - \varepsilon_{it-1}\right)$$

where y_{it} is the dependent variable of interest and X is the time independent vector of pre-program characteristics. They found that counties selected for TVA intervention saw a significant decline in agricultural employment and a significant increase in manufacturing employment. For example, the TVA's impact on agricultural employment was −7.1 percent and on manufacturing employment was 5.3 percent compared to non-TVA but characteristically identical counties. They found that by replacing agricultural jobs with manufacturing jobs, the median family income in TVA counties had also increased.

In assessing and explaining the overall effects of dams, Lipscomb, Mobarak, and Barham (2013) find that large dams in Brazil increased productivity and thus positively affected social welfare. Lipton, Litchfield, and Faures (2003) claim that much of the gains from dams were due to increased market integration in labor and input markets that were associated with the economies of scale that large dams made possible. Severnini (2014) argues that agglomeration impacts were behind the observed growth in those territories where large dams were built during the TVA era. Kline and Moretti (2014) investigate the general equilibrium effect of the TVA in a structural approach, showing that the TVA's direct investments yielded a significant increase in national manufacturing productivity that exceeded its costs, while the agglomeration gains in the TVA region were offset by losses in the rest of the country. In the case of India, Attwood (2005) lists the historical episodes of inflation and shocks to population growth, arguing that large reservoirs contributed to social welfare by preventing flooding in India.

6 Conclusions

Benefit–cost analysis on the benefits of dams has been inspired by the continuous debate on the value and design of dams and the challenge of the increased utilization of water resources for improved economic well-being while reducing the negative economic, social, and environmental side effects. This chapter reviews the impact of large dams. The results to date provide mixed evidence on the different topics. A dam's impact is likely to be heterogeneous in nature based on land quality, the qualifications of the individuals affected, and the purpose of the dam itself.

Further research should concentrate on identifying and disaggregating the direct and indirect impacts of dams. For example, it is possible that dams built in urban districts increase the welfare of the people living in the vicinity compared to dams built in rural districts, because the migration of people in response to a dam's construction in urban districts is systematically different from the migration of those living in rural districts. Both structural, general equilibrium approaches and reduced formed, partial equilibrium approaches should be encouraged.

New research can also examine the sometimes lackluster effects of dams. For example, dams may have failed to increase welfare because they caused too much resettlement, attracted too many poor people to catchment areas with marginal land quality, or the management of the dams failed to optimally allocate water or maintain a reservoir (due to a lack of effective sedimentation management). Furthermore, most of the empirical literature is localized and considers dams from countries such as Brazil, India, South Africa, and the United States. The ability to generalize from these countries' outcomes needs to be further investigated. Cross-country analyses, which are lacking, may provide some insight on the external validity of the results reported in previous literature.

There are also several other aspects of large dams that are not well understood. Given that reservoirs sites are exhaustible resources, how should a government faced with limited resources exploit them? There needs to be more investigation of temporal rules and optimal switching times from reservoirs to groundwater. Though thousands of dams have been constructed, there is very little research that analyzes the decision making process for governments before investing in the construction of dams.

To be effective, economic research on dams needs to be better integrated with knowledge and understanding from other disciplines. Some of the questions arising from economic research should influence the scientific research agenda on the performance and impact of dams. Furthermore, policy makers need more information as they approach the planning, construction, and management of new dams. As this survey shows, dams should take into account other activities, such as new technologies in water conveyance, conservation, and crop and hydroelectric production. New technologies that allow for the reuse of wastewater and for desalinization should affect dam and water management projects.

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