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Building Resilience to Climate Change in Sub-Saharan Africa through Irrigation Investments

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Introduction

Climate change seriously threatens the ability to achieve the Sustainable Development Goals (SDGs) in Sub-Saharan Africa (SSA), particularly food security goals for poor rural households. Rural development projects, including irrigation, can help minimize threats from climate change. With this in mind, to increase climate resilience, there has been considerable renewed interest in funding irrigation systems on the part of bilateral and multilateral donors. At the same time, there is recognition that many earlier irrigation projects did not succeed (Barghouti & Le Moigne, 1990; Bjornlund, Bjornlund and van Rooyen, 2020; Inocencio et al., 2007; Higgenbottom et al., 2021). Indeed, the large number of irrigation projects rolling out annually in the 1970's through the 1980's slowed to a trickle at the turn of the millennium, particularly investments in large-scale dam-based irrigation systems (Inocencio et al., 2007).

Despite previous irrigation investments, most countries in SSA remain extremely vulnerable to climate change due, in part, to near complete dependence on rainfed agriculture. AGRA (2019) notes that 6 percent of the total cultivated area in SSA is equipped for irrigation. While this may be an underestimate since official irrigation data in SSA generally fail to capture the full extent and diverse nature of water used for irrigation (Venot et al, 2021), it is clear that many SSA countries have untapped water resources that could be used for irrigation. Estimates suggest that in SSA only 28% of potentially irrigatable land actually has irrigation, which is substantially lower than North Africa (90%), South Asia (59%), Southeast Asia (55%), East Asia (98%) and Central Asia (74%) (Ringler, 2020).

Irrigation investments in the 1970's and 1980's were dominated by medium- to large-scale schemes operated by government irrigation authorities. This model relied on the government authorities to operate and maintain the entire scheme, though schemes also often relied on the authorities' ability to incentivize water users to maintain tertiary infrastructure, for instance through cleaning canals, and to respect land and water use rules, such as prohibiting grazing in the catchment area. By the 1980's, interest began to shift to smaller-scale schemes where Water Users Associations (WUAs) would assume greater responsibilities for operations and management, but by the mid-90's many international donors simply gave up on the cycle of build-deteriorate-rebuild that characterized many schemes, both small and large (Waalewijn et al., 2019).

Investments started building up again by the mid-noughts, with even greater emphasis on the involvement of WUAs through "irrigation management transfer" (IMT). In practice, the extent to which authority and responsibilities were devolved to WUAs differed significantly across schemes and countries.

Complete devolution often led to deteriorating conditions as found with state-level management and for similar reasons: poor design and/or low construction quality; lack of training of WUA leadership in operations and management; and lack of irrigator profitability (ill-developed value chains) necessary to incentivize users to pay water fees, participate in routine maintenance and repairs, and abide by land and water resource rules to ensure smooth functioning of the scheme. In particular, it became apparent that even with well-built infrastructure and well-functioning WUAs, some schemes simply did not generate the returns necessary to fund maintenance and repairs.

More recently, irrigation investments have moved towards two opposite approaches. The first is a return to larger-scale schemes, but located in areas where the necessary complimentary institutions and infrastructure for cash-crop farming are already operational (Kikuchi et al., 2020) or where infrastructure can be used for both hydropower and irrigation (You et al., 2013). Existing large-scale schemes tend to be operated under hybrid management, with professional management (state-owned enterprises or the private sector) responsible for the operations and maintenance (O&M) of the main and secondary infrastructure, WUAs having responsibility to collect user fees and to maintain tertiary, and sometimes secondary, level infrastructure. The objective of such schemes is to capitalize on economies of scope and scale at the higher scheme administrative levels, but empower WUAs to be responsive to its members and spur collective action.

At the opposite end of the spectrum, there is interest in expanding access to groundwater resources at the individual or small group level, generally using pumps (Balasubramanya & Lele, 2022; Ringler et al., 2020; Nakawuka et al., 2018). Altchenko and Villholth (2015) document the vast underground water resources in SSA suggesting there is potential to increase food production and productivity using groundwater. Other researchers argue that observers familiar with the experience of over-exploitation of groundwater resources in other countries in Asia and the Americas have been too cautious in warning of the dangers of over-exploitation in the SSA context (Rosa et al., 2018; Waalewijn et al., 2019; Xu & Beekman, 2019). Perhaps, but it stands to reason that setting up institutions to manage water rights from the beginning are less likely to run into problems further down the road, if and when aquifer levels begin declining and/or negative environmental impacts are being felt (Alley et al., 2016).

The extent to which these new investments in groundwater irrigation will improve farmers livelihoods and over what time frame will depend on the costs of acquiring and maintaining the extraction and distribution technologies and the pace at which the aquifer declines. Groundwater-based systems are often adopted by individual farmers, giving them greater flexibility in water and land-use decision-making

and avoiding the rigid and/or unreliable water delivery in scheme-based systems as well avoiding the higher costs associated with cooperating and coordinating in scheme-based systems. However, there can still be economies of scale over a range of small plot sizes, associated with well-building, water storage (e.g. ponds), tubes, and pump sizes (Acharyya, 2020; Mushtaq et al., 2009; Shah et al., 2021). Net benefits will also crucially depend on factors that affect the successfulness of all other irrigation projects, primarily access to input and output markets and to productivity- and market-related information, and opportunities costs of labor.

While the development paradigms undergirding irrigation investments over time have swung widely, the limited evidence suggests that timing of investments plays a limited role in explaining irrigation scheme performance – indicating that all paradigms tried so far have had limited success. For instance, Higgenbottom et al. (2021) evaluated the performance of 79 irrigation schemes in SSA that were constructed between 1944 and 2008. They reviewed project documents to obtain estimates of planned irrigated area and compared these with estimates of current scheme size derived from satellite-derived land cover maps. Their results are quite damning; the median scheme size was estimated to be just 18% of planned size, and 16 projects (20%) have completely failed. They also showed that scheme performance did not change over time; that is, recent schemes are as likely to suffer poor performance as older schemes.

In this paper, we review literature on the performance of different types of irrigation schemes, mainly restricting our attention to schemes found in SSA, though we do include wider geographic coverage for issues with more limited evidence in the SSA context. To organize the review, we use hypotheses generated from game-theoretic models that incorporate risk-averse producers subject to climatic risks in irrigation water supply. As described in the previous paragraphs, irrigation schemes – small, medium and large – often rely on WUAs to collect irrigators' fees and to maintain and repair lower-level infrastructure, so that these operate as a type of "common property management". Common property is subject to incentives by WUA members to underprovide public goods and overexploit common pool resources. In the case of irrigation schemes, over-exploitation is generally not an issue, but provision of public goods – in terms of maintenance and repairs – can be quite important. In contrast, individually-owned pump-based schemes using groundwater are not subject to under-provision of public goods, but over-exploitation can be severe.

There are many factors that affect the ability of water users to engage in collective action to reduce underprovision and overextraction. Starting with Ostrom's seminal work, many scholars have proposed a

number of hypotheses regarding the most critical factors affecting collective action, such as group size, heterogeneity of costs and benefits, the ability to monitor water use, and legally recognized land and water property rights, amongst others (Sandler, 1992; Ostrom, 1993; Vermillion, 1997; Meinzen-Dick et al., 2002). However, there has been much less work done to understand the likely impacts of climate change on collective action in general, and irrigation specifically. A game-theoretic model developed by McCarthy et al. (2004) leads to the hypothesis that greater exogenous weather volatility will reduce incentives for herders to overstock common pastures, similar to theoretical results found in Sandler & Sterbenz (1990) who show that exogenous harvest uncertainty reduces overexploitation of a common pool resource vis-à-vis the social optimum with no risk.

We build on the above work to develop two game theoretic models to consider impacts of increasing climate risks on collective action where actions increase production but also mitigate negative impacts of exogenous weather events. The first model analyzes under-provision of public goods and the second analyzes over-exploitation of a common pool resource. Section 2 provides the hypotheses that follow from these two models, while the modeling work is provided in Appendix 1. In section 3, we review the literature on the performance of different irrigation systems using the model hypotheses, while in section 4, we examine Project Completion Reports from irrigation projects funded by International Financial Institutions to extract factors associated with irrigation project performance. Section 5 then reviews the literature on the impact of access to irrigation on household livelihood outcomes. In section 6, we provide concluding observations and policy implications.

Two Game-Theoretic Models

We use two simple game-theoretic models to compare the impacts of risk on contributions to pure public goods (surface irrigation schemes) and on groundwater exploitation. Though simple, these models effectively generate interesting hypotheses that are more difficult to tease out in more sophisticated models.

For both models, we consider the impacts of parameters on outcomes under both non-cooperation and the social optimum. The social optimum captures the gains that could be made if irrigators were able to move from the worst outcome of non-cooperation, to the first-best outcome associated with perfect cooperation to reproduce the social optimum. Of course, there never is a social optimizer; rather, irrigators must construct institutions to achieve collective action goals of optimal public goods provision or groundwater extraction rates. Constructing institutions and effectively enforcing the rules of the game

entail real costs. The marginal gains from increasing collective action must then be equated to the marginal costs, and thus we do not expect "perfect" collective action to be achieved in practice (McCarthy et al., 2001). Costs of collective action are not explicitly included in the model, but we assume that higher costs of collective action will lead to lower public goods provision or greater over-extraction of groundwater[1]. Below we summarize the models and resulting hypotheses.

Public Goods (Surface water) Game

In the public goods game, risk-averse irrigators choose how much of a public good to provide to maintaining irrigation infrastructure, and these maintenance activities lead to both greater and more stable water availability. Incentives to provide public goods is higher at irrigation sites where the expected marginal impact of water on crop production is relatively high, and the ability of maintenance activities to reduce water variability is relatively high. Increasing risk aversion at first also increases public goods provision, but at very high levels of risk aversion and high water variability, irrigators will reduce public goods provision and perhaps even abandon their plots. So, in locations where climate change induces large increases in extreme weather events that translate into greater irrigation water volatility, public goods provision may decrease, especially if public goods have limited impacts on reducing that volatility. Public goods provision will also be higher where value chains are well-developed and opportunity costs of labor are relatively low, and where transactions costs of collective action are relatively low.

Groundwater Game

In the groundwater game, risk-averse irrigators must choose how much irrigation water to extract, given that water extraction increases average costs of extraction and increases volatility of groundwater levels. Incentives to over-extract groundwater are lower where risk-aversion is higher, exogenous water variability is higher and where extraction leads to relatively large increases in the volatility of water availability. Climate change-related impacts on the frequency and severity of extreme weather events that subsequently affect irrigation water volatility should reduce incentives to over-extract and to collectively act to manage groundwater resources[2]. However, more favorable market conditions, high

[1] We thus do not consider whether increased climatic risks will directly affect transactions costs of collective action. For instance, the ability to monitor irrigators actions may become more difficult when extreme weather shocks become more frequent and severe. As far as we are aware, there is no evidence of the impact of greater risks on the ability to engage in collective action for irrigation management, and so this potentially important issue is left for future research.

[2] Starting from low water volatility and relatively low risk-aversion, increases in water volatility may increase over-extraction under non-cooperation, since the individual irrigator only internalizes one's own value from reduced

marginal value of water in crop production, and low marginal costs of extraction will increase incentives to over-extract. The latter can be juxtaposed with the provision of public goods, where more favorable value of production conditions increase public goods provision even under non-cooperation. At the same time, more favorable economic environments also increase the incentives to collectively manage groundwater resources (they increase the gains to cooperation), and so the overall impact will depend on the transaction costs of collective action.

Extension 1: Opportunity Costs of Labor

In our simple models summarized above, we only allow for the farmer to choose contributions to the public good or groundwater extraction rates. This was done to specifically highlight the impacts of risk aversion and water variability on outcomes, which can be obscured in more sophisticated models. But farmers make other input and resource allocation decisions, and in the context of irrigation project performance, opportunity costs of labor are likely to be important in many cases. If farmers have access to other income generating opportunities, we hypothesize that less labor will be devoted to production and to public goods provision, and even to groundwater extraction. On the other hand, limited off-farm opportunities should increase public goods provision but also groundwater extraction, all else equal.

Extension 2: Construction

Surface water schemes require initial investments in infrastructure to distribute water, including reservoirs for dam-based schemes, infrastructure to divert water in river-based schemes, canals to distribute water, and drainage infrastructure to manage excess water, to name but a few. In most cases, incentives to provide public goods to maintain poorly constructed infrastructure will be lower than incentives to maintain well-built infrastructure, because even though marginal returns may be high, marginal costs are likely to be much higher, or even prohibitive. Many irrigation schemes have in fact been abandoned after only a few years in operation, with some evidence to suggest construction was so poor that maintenance could not generate enough net marginal benefits to be sustained (Adekunle et al., 2015; Birner et al., 2010; Saidou & Kossou, 2009; Shayamano, 2016; Webb, 1991).

volatility due to lower extraction, but does not internalize the benefits to other irrigators from reduced volatility. In the remainder of the paper, we presume that the overall impacts (on average production and volatility of production) will reduce incentives to over-extract groundwater.

Extension 3: Transactions Costs of Collective Action

Both the theoretical literature and empirical evidence suggests that heterogeneity in costs and benefits across irrigators makes it more difficult to achieve collective action. Heterogeneity makes it more difficult to craft rules that reflect that heterogeneity in a way that is seen as credible and fair given imperfect information amongst users (Baland & Platteau, 1997; Bardhan, 2000; Dayton-Johnson, 2000; Johnson & Libecap, 1982; Varughese & Ostrom, 2001; Tang, 1991). The overall evidence on the impact of social, cultural and economic heterogeneity, with two main reasons identified in the literature. First, local governance structures can overcome any negative impacts of economic or social heterogeneity, by building trust amongst users and trust in leadership and effective mechanisms are in place to ensure compliance (Adhikari & Lovett, 2006; Meinzen-Dick et al., 2004; Poteete & Ostrom, 2004; Waalijen et al., 2018). Second, heterogeneity is often correlated with the existence of highly profitable irrigators who find it optimal to provide public goods even under non-cooperation; gains to these irrigators are sufficient to achieve optimal provision despite free-riding by less profitable irrigators (Olson, 1965; Cornes & Sandler, 1996; Nakano & Otsuka, 2017). Similarly, mutual trust can be more difficult to achieve when irrigators share different socio-cultural values and have limited social bonds (Alesina et al., 1999; Bardhan & Dayton Johnson, 2002; Miguel, 2000).

The number of users in the system is often associated with greater over-extraction. For public goods, however, an increase in the number of users may initially increase public goods provision up to a certain level, at which point provision may decline (Banerjee, Iyer & Somanathan, 2007; Oliver et al., 1985; Takayama et al., 2018). For instance, in very small irrigation schemes, the required public goods contributions per person may be very high. Moving to larger schemes can defray per person maintenance costs but coordination and monitoring costs will also increase. At some point increasing transactions costs of collective action will overwhelm decreasing maintenance costs, leading to low overall provision.

Monitoring costs can also differ substantially across different types of irrigation schemes and across available (and cost effective) monitoring technology. Where water use is not metered, irrigators can often find ways to take more water than they are supposed to and/or acquire water at times when it is most needed, even if it is not scheduled. Depending on the scheme layout and how often irrigators go to the fields, actual water use might be very difficult to monitor. Groundwater extraction poses even greater difficulties since water is pumped to individual fields and impossible to monitor without meters.

Ostrom's seminal works (1990, 1993) on governing the commons and design principles of irrigation institutions outline "design principles" that can reduce the transactions costs of collective action. Project activities that attempt to lower these costs include WUA -level capacity building that improves trust amongst users and potentially enables the WUA leadership to more effectively address heterogeneous users and uses; water fees and public goods contributions that are proportional to irrigated landholdings; other activities to build social cohesion; investments in mechanisms to help monitor water use and public infrastructure conditions; and the extent to which WUAs and individual groundwater users are legally recognized and integrated into the structures and decision-making processes of the larger water use and management system.

Summary of Hypotheses:

Surface Water Schemes

1. Incentives to collectively provide public goods will be higher as climate change risks increase when the positive marginal impacts of public goods on reduced water variability are large relative to the impacts of increased climate risk on the risk premium.
2. Incentives to engage in collective action will generally be more favorable when heterogeneity in socio-economic characteristics among irrigators is low, where number of irrigators is relatively small (perhaps after a certain point), and where monitoring is relatively inexpensive. Incentives to engage in collective action will also be greater where WUA leadership has the capacity to make, monitor and enforce collective action taking into account heterogeneity in costs and benefits amongst irrigators, thereby lowering transactions costs of collective action.
3. Incentives to collectively provide public goods will be higher where water has relatively high marginal impacts on yields; where markets are well-developed with relatively high output prices and low input prices; and where opportunity costs of on-farm labor are relatively low.
4. Incentives to collectively provide public goods will be greater where non-irrigation based risks are relatively low (e.g. access to well-developed markets that dampens price swings, land tenure is secure, violent conflicts are rare).
5. Incentives to provide public goods will be higher where irrigators and WUAs have the knowledge and skills to operate and manage the scheme, as well as the fiscal capacity and ability to access goods and services to maintain and repair the infrastructure.
6. Incentives to engage in collective action will be higher where the infrastructure design and construction is of relatively high quality.

Groundwater

7. Incentives to invest in groundwater irrigation and to collectively manage groundwater extraction will be higher where climate change-related risks are relatively low.
8. Incentives to collectively manage groundwater extraction will generally be more difficult when heterogeneity in socio-economic characteristics among irrigators is high, where number of irrigators is large, where there are multiple users and uses of groundwater, and where monitoring is costly.
9. Incentives to invest in groundwater irrigation and collectively manage groundwater extraction will be higher where water has relatively high marginal impacts on yields; and, where markets are well-developed with relatively high output prices and low input prices.
10. The ability to collectively regulate groundwater extraction will be more effective where legally recognized mechanisms exist to monitor groundwater levels, legally backed fora operate to disseminate information on groundwater levels and negotiate potential actions on the part of irrigators and other groundwater users, and where government enforcement is effective when needed.

Evidence in Support for Hypotheses

We did not perform a rigorous systematic review, but we did begin with certain keyword searches, and built on these by evaluating the citations referenced. For instance, using google scholar search, we used the following: africa empirical evidence intitle:maintenance intitle:irrigation, which returned but 10 results. Many studies focused on just a few case studies limiting external validity, while the degree of rigor varied quite a bit across the literature. Given that we are looking for evidence of specific correlates with irrigation system performance, we included all available evidence without trying to ascertain the quality of each methodological approach. Given that there is very little in the way of rigorous academic research assessing the hypotheses generated here, triangulating evidence on correlates of irrigation system performance provides still provides valuable insights about those correlates on which there is broad agreement, and helps identify key knowledge gaps.

Irrigation Schemes

H1. Incentives to collectively provide public goods will be higher as climate change risks increase when positive marginal impacts of public goods on reduced water variability are large relative to the impacts of increased climate risk on risk premium.

Though evidence is relatively scarce, studies that do consider variability of irrigation water supply suggest that more volatile irrigation water availability dampens incentives to supply public goods, which suggests that public goods have a limited impact on reducing volatility relative to the negative impacts of increased costs of bearing risk for risk-averse farmers. Kahuro (2012) finds that reliability of water supply is positively correlated with participation in maintenance activities through both higher labor provision and greater share of irrigators paying fees, as do Maleza & Nishimura, 2007. Chidenga (2003) finds that lack of reliable water reduces contributions to maintenance in schemes in Zimbabwe. In Benin, Totin et al. (2014) document the abandonment of surface water diversion scheme land in the lowlands in favor of individual groundwater pumping upland for farmers that had access to upland plots; the authors surmise that this is related to more reliable water from groundwater pumping versus less reliable surface water. The World Bank (2021) notes that unreliable irrigation water supply in Tunisian schemes, often due to "dilapidated infrastructure", led to low fee recovery, resulting in an ever-deteriorating systems. However, Sharaunga & Mudhara (2018) and Muchara et al. (2014) show that farmers who experience severe water shortages are more likely to contribute labor to maintenance particularly if they also farm relatively larger plots, suggesting that in some cases, maintenance can generate relatively high marginal benefits in terms of increasing reliability of irrigation water.

The World Bank (2021) discusses the allocation of risks across stakeholders in the case of a large-scale irrigation scheme, Guerdaine, in Morocco, and argue that this allocation of risk increases incentives to maintain and repair the system at different operational scales. More specifically, the scheme is operated by a consortium of private investors who have responsibilities to maintain the main and secondary infrastructure, while irrigators have responsibility for tertiary infrastructure. In the event of water scarcity, irrigators are responsible for a first layer of risk, the private consortium for a second-layer, and the government for the third "catastrophic" layer. This protects both irrigators and the private consortium from full impacts of catastrophic risks, and the authors argue that this risk-sharing is one of the primary reasons that the scheme functions well.

H2. Incentives to engage in collective action will generally be more favorable when heterogeneity in socio-economic characteristics among irrigators is low, where number of irrigators is relatively small (perhaps after a certain point), where monitoring is relatively inexpensive, and where transactions costs of collective action are relatively low.

Overall the literature supports the notion that at least certain types of heterogeneity have negative impacts on incentives to engage in infrastructure maintenance (Chidenga, 2003; Totin et al., 2014; World Bank, 2021). Totin et al. (2014) provide an interesting example of how difficult it is to draw general hypotheses regarding the impact of heterogeneity on collective action. The authors note that heterogeneity in power relationships reduces incentives to cooperate, since powerful leaders and privileged farmers do not contribute labor and often do not pay fees and yet remain unsanctioned, while less connected farmers are regularly fined. At the same time, the authors noted that contributions to maintenance were generally higher in the largest scheme that encompassed irrigators from multiple villages, arguing that the more formal management structure reduced the influence of elites in O&M and fostered greater cooperation amongst irrigators.

A number of studies also consider heterogeneity in benefits to more profitable farmers who tend to own larger irrigated plots versus subsistence irrigators in the same scheme. The World Bank (2021) observes that in Mali's OdN scheme, some farmers are engaged in high-value contract farming while others continue with subsistence farming. The authors surmise that this heterogeneity may reduce incentives to effectively maintain irrigation shared infrastructure. On the other hand, Nakano & Otsuka (2017) find the heterogeneity in plot size holdings was associated with better canal maintenance, which the authors attribute to the "small exploiting the rich" (Olson, 1965; Cornes and Sandler, 1996; Buchholz & Sandler, 2016). This outcome is related to heterogeneity, but it is also distinct from trying to successfully provide public goods when costs and benefits differ substantially across irrigators; here, it is possible that the non-cooperative outcome leads to good maintenance because irrigators with large plots have sufficient incentives to do so even under non-cooperation.

Somewhat surprisingly, there is limited evidence of the impact of the number of irrigators or size of the scheme on irrigation scheme performance. There is a perception by observers that large-scale schemes are more likely to fail, but limited empirical evidence to substantiate that claim. As discussed above, Higginbottom et al. (2021), collected data on 79 irrigation projects implemented in SSA from 1944 to 2008. Splitting the observations into quartiles based on planned size, we calculate the percentage of current irrigated area that was planned, the percentage of projects that have completely failed, and the

percentage of projects whose current land cultivated is greater than planned. Results are presented in Table 1 below.

Table 1: Measures of Irrigation Performance Against Planned Size

Quartiles	Performance		
	% Planned Area		
Range in Hectares	Currently Irrigated	% Failure	% Surpassed Plan
0-1400	60%	5%	25%
1401-5100	19%	35%	0%
5101-17265	32%	21%	21%
17265-900000	35%	20%	10%

Table 1 suggests that larger schemes do perform more poorly in terms of planned area currently irrigated and have more failures than those found in the 1st quartile, but the worst performance is found in the 2nd quartile, while the 3rd and 4th quartiles perform similarly. Interestingly, projects in the 3rd quartile are almost as likely to exceed planned area as those in the 1st quartile, while the 2nd quartile again performs worst.

With respect to monitoring costs, in small schemes, especially those where the irrigation infrastructure and irrigated plots fall within the same contiguous area, monitoring infrastructure and whether canals are clean is fairly straightforward, but enforcing participation in maintenance can still pose problems. In other schemes, it is more difficult to monitor whether irrigators are taking more than their share of water, especially irrigators situated at the head of the command area (Fanadzo & Ncube). This is particularly problematic in systems where gates are manually operated and where gates cannot be locked, which dampens incentives to provide collective maintenance (Chidenga, 2003). Additionally, in some river diversion schemes, water distribution infrastructure from the river to irrigated plots may cross over non-irrigated public land. In these cases, it is difficult to monitor water thefts, which again dampens incentives to provide collective maintenance (Adekunle et al., 2015; Chidenga, 2003).

With respect to transactions costs of collective action, a number of studies find that WUAs are more successful in managing irrigators incentives to provide public goods where they have legal recognition and where there is at least some level of formality to the WUA organization. In part, greater formality may help guard against poor leadership, elite capture and possibly corrupt practices by the leadership

(Vermillion, 1997; Chidenga, 2003; Ferguson & Mulwafu, 2004; Mati et al., 2011; Kahuro, 2012; Totin et al., 2014). However, others have noted that externally imposed by-laws not drafted by community members nor in consultation with them, may have little meaningful impact on O&M (Meinzen-Dick, 1997; Samakande et al., 2002; Yami, 2013). WUA performance is also higher where perceived capacity of leaders and trust in leadership is high (Akuriba et al., 2019; Meinzen-Dick, 1997; Sonda & Ngaruko, 2017), and where the WUA has established effective mechanisms to punish those who fail to comply with labor and user fee requirements (Chidenga, 2003; Totin et al., 2014; Waalijen et al., 2018). Collective action is also more likely where irrigators perceive that water distribution and collective contributions are seen as fair (Adenkule et al., 2015; Shayamano, 2016; Totin et al., 2014).

H3. Incentives to collectively provide public goods will be higher where water has relatively high marginal impacts on yields; where markets are well-developed with relatively high output prices and low input prices; and where opportunity costs of on-farm labor are relatively low.

Almost all of the evidence supports the hypotheses that maintenance is more likely where marginal production benefits are positive; that is, where net profits are relatively high; access to complimentary institutions that provide information and access to markets is high, opportunity costs of labor are relatively low; and where water is relatively scarce.

With respect to marginal production benefits, a large number of studies note that collective action for O&M tends to be more successful when irrigators grow cash crops, which tend to generate higher marginal net revenue than subsistence crops (Byiringo et al., 2020; Emaleaf, 2017; Sonda & Ngaruko, 2017; Maleza and Nishimura, 2007; Sharaunga & Mudhara, 2018; World Bank, 2021). Additionally, farmers with larger plot holdings are often found to contribute more to collective labor since the marginal benefits to maintaining shared infrastructure will be higher for those with larger plots (Arun et al., 2012; Emaleaf, 2017). As noted above, Nakano & Otsuka (2017) show that irrigation blocks (managed by lower level WUAs with the responsibility for maintaining tertiary canals) with greater heterogeneity in irrigated plot sizes were more likely to have better maintained canals. The authors surmise that, even with free-riding, larger holders have strong economic incentives to maintain canals. Having larger plots is also often associated with cash crop production, which increases marginal benefits still further (Legoupil, 1985; van Averbeke et al., 2011). Sharaunga & Mudhara (2018) document that farmers who perceive that soil quality of their irrigated plots is relatively good are more likely to contribute more labor to maintenance.

A number of studies have also documented that schemes situated where farmers have access to complimentary services, such as extension, well-developed input and output value chains, and credit are

more likely contribute to collective O&M, which is in part correlated with the decision to grow cash crops and thus achieve higher marginal net benefits (Legoupil, 1985; Ojendal & Bandeth, 2016; Dorward & Kydd, 2010; Totin et al, 2014; Fanadzo & Ncube, 2018; Masasi & Ngombe, 2019).

Opportunity costs can substantially affect incentives to engage in collective action. For instance, high opportunity costs of labor and cash can reduce the number of days contributed towards collective labor and lower the likelihood of paying fees (Dayton-Johnson, 2000; Saidu et al., 2014; Totin et al., 2014). On the other hand, households with relatively low opportunity costs such as large households, or those more dependent on irrigation income or agricultural income more broadly (signaling limited opportunity costs) are more likely to contribute to collective labor efforts (Kahuro, 2012; Emaleaf, 2017). More frequent and severe weather shocks may well increase the opportunity costs of labor, favoring non-farm income sources that are less weather dependent; however, we found no empirical evidence to support this observation.

With respect to water scarcity, only a few studies of SSA-based schemes mention relative water scarcity. This may be due to two reasons. First, many schemes are river-based diversion schemes, which generally face fewer water scarcity issues than dam-based schemes that are more reliant on seasonal rainfall. Secondly, researchers tend to conflate “average” water availability with water supply variability. Our model suggests that scarce, but stable, water supplies favor collective action when collective maintenance increases water availability on average but where maintenance has limited impacts on water volatility. Totin et al. (2014) evaluate the performance of 3 case study sites in Benin where irrigated rice production is practiced in gravity-based surface water schemes, and document that collective action to clean canals and pay fees is higher at the scheme where water scarcity was relatively high. Vandersypen et al. (2006) evaluate the performance of sub-WUAs to maintain tertiary canals in a large river-diversion scheme in Mali (the Office du Niger scheme); the authors surmise that the abundant water supplies likely dampen incentives to invest in canal maintenance. The World Bank (2021) also argued that abundant water supplies reduced incentives to maintain and repair irrigation infrastructure at the same Mali scheme. The same World Bank (2021) also argues that the successful transfer of O&M to WUAs in Peru was largely successful in part due to the extreme dependency of farmers on irrigation water in a scheme located in the North Coast Desert. Extreme water scarcity in Tunisia and Morocco is also mentioned by the World Bank (2021) as a critical factor motivating irrigator participation in maintenance and/or paying fees. The examples from Peru, Tunisia and Morocco are irrigation schemes that rely on more stable water sources.

H4. Incentives to collectively provide public goods will be greater where non-irrigation based risks are relatively low (e.g. access to well-developed markets that dampens price swings, land tenure is secure, violent conflicts are rare).

Tenure security affects the incentives to invest now to obtain future benefits. To the extent that repairs and maintenance generate benefits over multiple cropping seasons, tenure security may affect expected marginal net benefits. Most studies that consider tenure security have generally found that various metrics of tenure security are associated with collective contribution to O&M (Damianos & Giannakopoulos, 2002; Meinzen-Dick, 2014; Mutambara et al., 2016; Fanadzo & Ncube, 2018; Sharaunga & Mudhara, 2018; Shayamano, 2016). Similarly, other authors argue that access to markets that ensure more reliable services and less volatile prices increase incentives to provide public goods (van Averbeke et al., 2011; Totin et al., 2014; Öjendal & Bandeth, 2016).

H5. Incentives to provide public goods will be higher where irrigators and WUAs have the knowledge and skills to operate and manage the scheme, as well as the fiscal capacity and ability to access goods and services to maintain and repair the infrastructure.

Even if collective action were costless, the ability of WUAs and irrigators to effectively operate, manage and maintain irrigation systems will be a function of the human resources, financial capacity, and network connections. For instance, even gravity-based based surface water systems require management skills to secure the resources required for major repairs. A number of studies support the hypothesis that knowledge and skills are critical for successful O&M at multiple levels of administration (van Averbeke et al., 2011; Kahuro, 2012). At the individual irrigator level, Kahuro (2012) documents that lack of technical knowledge needed to understand the value of routine maintenance is correlated with a lower likelihood that an irrigator contributes to maintenance activities.

Van Averbeke et al. (2011) point to the collapse of many schemes after IMT in South Africa as being due, at least in part, to the fact that many of these schemes were based on sophisticated river diversion designs coupled with overhead sprinkler systems that had replaced older canal-based systems in the 1970's and 80's. The overhead-based systems require expensive and sophisticated management, maintenance and repair, which the local irrigator groups were in no position to provide. The authors surveyed extension agents to obtain information on what they saw as major constraints to well-functioning and maintained irrigation system, and they identified management, human capital and organizational capacity as being the primary constraint. The authors then point to the work done by Legoupil in 1985, commissioned by the Water Resource Council (a government agency), who stated that human and institutional constraints were the most important to address in 1985. In fact, WRC commissioned 16 additional studies between

1992 and 2011, almost all of which stressed the poor performance of O&M. And yet, future projects continued to take a technical engineering approach, with insufficient training and capacity building for irrigator groups responsible for O&M. The authors frustration with this state of affairs is quite palpable; especially since many others had also stressed the need for significant training of WUA leaders and irrigators in O&M starting when the infrastructure is being built (Chancellor & Hide, 1996; Chidenga, 2003). Relatedly, Van Averbeke et al. (2011) also argue that scheme designs need to reflect both irrigators capacity to implement O&M (even with training) and the ability of irrigators to afford fees, which is clearly related to their net profitability. For instance, schemes that will be used for subsistence or garden vegetables should require minimal resources for O&M, e.g. gravity-based canal designs. More sophisticated systems can only be financially viable where high-value crop production can cover the costs associated with high skill requirements in O&M and financial capacity to ensure expensive, though routine, maintenance and repairs.

Relatedly, performance of schemes that are part of an IMT program depends critically on the clarity and logic of assigned roles and responsibilities across government agencies that remain involved as well WUAs and individual irrigators. The World Bank (2021) argues that the initial decentralization model used by the government of Tunisia led to confusing and overlapping operational roles across government agencies and water user groups, leading to lack of accountability on the part of service providers and unreliable service delivery, which in turn led to poor cost recovery. Alternatively, the Guerdaine project in Morocco, operating as a public-private partnership, is considered a particularly successful large-scale irrigation project in part due to a supportive legal and regulatory framework, and to a cohesive structure of roles and responsibilities across government agencies, the private sector consortium, and WUAs (World Bank, 2021).

An IMT program should also be based on the principles of “optimal devolution” or “subsidiarity”, where authority, roles and responsibilities are assigned at the administrative level that is the most cost effective in providing O&M services (Andersson & Ostrom, 2008; Berger et al., 2007; Blomquist et al., 2010; Brousseau et al., 2012; Meinzen-Dick, 1997). Full devolution of responsibility for O&M of an entire irrigation scheme simply will not work in more sophisticated schemes, and requires a different institutional structure, with well-defined roles and responsibilities (van Averbeke et al., 2011; Cambaza et al., 2020; Chidenga, 2003). van Averbeke et al. (2011) document the collapse of many systems in South Africa following a “chaotic and rushed” IMT process. Marcus (2007) discusses the IMT process in Madagascar, highlighting that the rapid and chaotic decentralization over water resource management,

including irrigation, has basically transferred all responsibilities to the communities, while the communities obviously do not have the requisite financial, technical and administrative expertise required to assume these responsibilities. The justification given was that the transfer would shift irrigators from subsistence to high value crops, with limited appreciation for the complimentary institutions required to foster such as shift. Overall, the evidence suggests that for most schemes, the government, parastatal or higher-level organization must retain certain roles and responsibilities, especially those associated with economies of scope or scale, e.g. maintenance and repairs that require heavy machinery, highly skilled labor and/or procurement of replacement parts.

H6. Incentives to provide public goods will be lower where the infrastructure design and construction is of relatively low quality, or is built in such a way that even "perfect" cooperation will never be able to optimally maintain and repair the infrastructure from a social planner's perspective.

There are two distinct aspects to infrastructure design and construction that can affect incentives to provide maintenance and repairs. The first is more commonly mentioned and relates to the quality of built infrastructure. Poorly placed intake valves, improper drainage, use of poor quality materials are some of the few issues that have been mentioned (World Bank, 2015; Adekunle et al., 2015; Saidou & Kossou, 2009; Shayamano, 2016; Osman, 2015; Webb, 1991). If the infrastructure already requires a good deal of repairs or retro-fitting after only a few years in operation, the incentives to maintain that infrastructure are going to be lower due to lower marginal benefits from maintenance.

The second issue is building infrastructure for which it will never be financially viable to maintain. This issue is related to the optimal IMT structures discussed in the preceding section. Smallholders in isolated areas, with limited support and access to complimentary institutions, and thus focusing on subsistence crops are often not even able to cover routine maintenance of more sophisticated schemes. Averbeke et al. (2011) provide a clear example, showing that the pump-driven overhead irrigation systems in South Africa simply cannot be operated and maintained in schemes that are relatively isolated, where irrigated land per household is well below 2 hectares on average, and where irrigators focus either on subsistence crops or vegetables for own consumption on very small garden plots. The authors note that, while not perfectly managed, gravity based systems with canals are more likely to be operational in South Africa than overhead schemes. While gravity-based canal systems are the most expensive up-front, the authors argue that they do tend to last longer. Alternatively, You et al. (2011) evaluate potential returns to large-scale irrigation schemes, but only consider schemes that would obtain water from reservoirs that also generate hydro-electric power. Under this type of conjunctive use and assuming that they hydro-electric company would be responsible for reservoir maintenance, irrigators should be able to afford maintenance

of the secondary and tertiary infrastructure. Nonetheless, there are relatively few sites suitable for both hydropower and irrigation.

Relatedly, recent work has emphasized the overly optimistic estimates of net profitability in irrigation proposals than what the past 50 years of evidence has shown (Higginbottom et al., 2010; Higginbottom et al., 2021; Merrey, 2020; Redicker et al., 2022). Even schemes that are considered successful, such as the Mwea irrigation scheme in Kenya, would generate relatively low returns if constructed now. This might seem incidental, but the renewed interest in funding very large-schemes in response to climate change has caused alarm amongst experts who are concerned that lessons from past failures may be pushed to the side and the potential for future failures starts at the project proposal stage (Merrey, 2020; Higginbottom et al., 2021).

Those writing project proposals for international financing institutes and donor agencies face strong incentives to develop very large projects with optimistic estimates of benefits and costs, and irrigation projects are no exception. As highlighted in section 4, a review of irrigation project completion reports suggests that most previous irrigation project proposals were not well-prepared, with rudimentary understanding of the availability of firms with the requisite expertise to construct irrigation infrastructure, the required regulatory framework to allocate clear roles and responsibilities for supervising construction and training those to whom O&M responsibilities will be transferred, and the institutional context that determines the net profitability of irrigators (markets, credit, land tenure, maintenance and repair service providers, amongst others). Future project proposals should be able to adequately address the substantial issues with strong empirical support documented above to avoid future failures. And, they must also squarely address new and arising issues, particularly the impact of climate change on the appropriate design and O&M of proposed schemes.

Ground water Hypotheses

H7. Incentives to invest in groundwater irrigation and to collectively manage groundwater extraction will be higher where negative impacts of increased climate change-related risks are relatively low.

Evidence of the impacts of exogenous groundwater variability and risk aversion on incentives to invest in groundwater irrigation and collectively manage groundwater is very scarce. And yet, many groundwater sources used in Africa are relatively shallow and therefore rainfall dependent. Agutu et al. (2019) model groundwater levels and temporal variability of 9 aquifers in East Africa, and find that rainfall is a driving factor of temporal variability in these aquifers. Gowing et al. (2016) establish that shallow groundwater

does vary though not as much as rainfall in an Ethiopian case study. Theoretically, we would expect that greater groundwater variability would limit incentives to invest in groundwater, particularly investing in expensive technologies such as motor pumps with high fixed and variable costs; but, we found no studies that evaluated differential adoption rates of different groundwater pumping systems directly.

A number of authors have documented that rainfall variability and weather extremes increase the likelihood of investing in groundwater irrigation versus relying on rainfed crop production, consistent with incentives to invest in more stable water supply. Osewe et al. (2020) find that farmers' experiences with drought increases incentives to invest in groundwater irrigation. Increasingly erratic rainfall patterns led to the expansion of shallow groundwater irrigation in northern Ghana (Laube et al., 2012). Wijnen et al. (2018) argue that more research needs to be invested in locating "weather-independent" groundwater resources, as many groundwater irrigators currently rely on shallow aquifers, though they do not explicitly link variable water supplies from shallow aquifers to the decision to invest in groundwater. The evidence suggests that groundwater – even from shall aquifers – may be less variable than rainfall, but overall, there is no evidence to assess whether greater groundwater variability reduces incentives to invest in groundwater irrigation itself (whether investments are greater in areas with less versus more groundwater variability).

H8: Incentives to collectively manage groundwater extraction will generally be more difficult when heterogeneity in socio-economic characteristics among irrigators is high, where number of irrigators is relatively high; where there are multiple uses of groundwater, and where monitoring is relatively costly.

Wijnen et al. (2018) broadly argue that the multiple uses and users of groundwater, combined with lack of knowledge over the size and scope of such resources and concomitant sustainability concerns, are major reasons why smallholder groundwater irrigation is a low priority for most governments. The World Bank (2021) documents a case in Mexico, where aquifer management councils were established in 1998 but have not been effective in limiting over-extraction. Both large landowners and smallholders ("ejidatorios") rely on groundwater concessions, as do industrial, commercial and municipal domestic water supply (many uses and users). Larger farmers are also involved in the lucrative horticultural markets and rely exclusively on groundwater, while the smallholders tend to farm subsistence crops, maize and beans. The wide heterogeneity of interests, the authors argue, likely contributes to the ineffective management of groundwater resources; in fact, average annual drawdown is extreme at 40% of recharge.

With respect to monitoring, it is often very costly to adequately monitor groundwater resources, especially in locations where the groundwater system is complex and the hydrogeology is not well known

(Alley et al., 2011; Dessalegn & Merrey, 2015; Pavelic et al., 2012; Wijnen et al., 2018; World Bank, 2017). As a number of authors have noted, there is limited information on groundwater systems in most sub-Saharan Africa; generating this evidence would be a pre-requisite for establishing a regulatory framework to address potential over-extraction in the future (Takeshima et al., 2010; Wijnen et al., 2018). Abric et al. (2011) found that farmers in Nigeria and Niger felt that over-extraction was leading to declining water levels after projects promoting groundwater pumping had been implemented, and noted that data from piezometric monitoring was not always collected systematically by the government agency in charge.

H9: Incentives to invest in groundwater irrigation and collectively manage groundwater extraction will be higher where water has relatively high marginal impacts on yield; and where markets are relatively well developed offering relatively high output and low input prices.

Most evidence for groundwater irrigation supports the hypothesis that greater profitability does increase individual incentives to invest in irrigation equipment, though evidence of impacts on managing groundwater extraction is very limited in the SSA context. Osewe et al. (2020) find that, in Tanzania, higher net profitability incentivizes farmers to invest in irrigation as we expect; cash-crop irrigation (horticulture) dominates, and there are well-developed value chains that are accessible depending on the farmers location. The authors note that there should be enforceable regulations to protect the environment and rights of other users, but this observation is without evidence and without a link to profitability per se. Colenbrander & van Koppen (2013) note that farmers often "disadopt" motorized irrigation pumping in Zambia, since farmers find it difficult to find mechanics and/or materials to make repairs.). There is optimism that solar-powered pumps, whose prices continue to decline, may increase profitability of groundwater irrigation, though empirical evidence remains scarce. Solar-powered pumps do require a relatively high fixed-cost investment, but pumping costs are then limited to maintenance and repair thereafter. Where diesel costs are high, solar can provide an attractive alternative if financing modalities can be developed (Shah et al., 2020; Xie et al., 2021).

The World Bank has supported a number of "fadama" projects in Nigeria since the 1990's through the late 2010's; while this project has a large range of activities, one of its primary goals was to increase irrigation using shallow groundwater. Many reports characterize the project as successful (Abric et al., 2011; Hima et al., 2016; World Bank Implementation Completion Report, 2020). A study prepared for the Nigerian government of the fadama project notes that 81.5% of respondents noted that canals were not functioning at the time of the 2019 survey, while nearly 100% said that sprinklers were not functional (Dayo et al., 2020). While the authors do not make a direct link with market conditions, they do note in a separate section that many farmers found it difficult to market crops such as onions and tomatoes,

particularly when they did not have access to post-harvest storage facilities. Abric et al. (2011) found that poor marketing conditions as negatively impacting irrigated onion production in Niger. Studies using the World Bank's LSMS-ISA data for Nigeria also find that irrigation has not expanded very much since at least 2010, finding that just 2.5% - 3% of households irrigating any land (Takeshima, 2016; Villacis et al., 2022). Villacis et al. (2022) suggest that, in addition to thin markets, a major factor hindering irrigation investments in the drier northern regions is the violent conflicts and associated risks of losing crop production or even access to land. Secure land tenure more broadly has also been identified as a barrier to adoption of groundwater irrigation in other contexts (Wijnen et al., 2018).

Evidence outside of SSA indicates that net profitability actually exacerbates groundwater extraction, which is consistent with non-cooperative behavior and high transaction costs of collective action to manage groundwater resources. For instance, fuel subsidies that lower extraction costs in India are argued to increase over-extraction and impede efforts to regulate groundwater use (Chauduri et al., 2021 and references cited therein), while World Bank (2021) argue that growers in Mexico of high value horticulture crops destined for the lucrative US market have limited incentives to actively participate in government schemes to manage over-extraction.

H10: Ability to collectively regulate groundwater extraction will be more effective where legally recognized mechanisms exist to monitor groundwater levels, legally backed fora operate to disseminate information on groundwater levels and negotiate potential actions on the part of irrigators and other groundwater users, and where government enforcement is effective when needed.

The Mexican example provided in World Bank (2021) discusses the regulatory structures involved and the ability to monitor groundwater use. The aquifer management committees in Mexico have very limited authority and function mainly as intermediaries between farmers and the state irrigation authorities. Monitoring has been expanded, but illegal well operations and enforcement of existing concession limits remains weak. Combined with the heterogeneity of uses and users, these features limit the ability of the government to effectively manage groundwater. Currently, many states in India are pursuing participatory groundwater management that attempts to include the voices of all relevant stakeholders, though it remains too early to tell how effective such a shift may be (Argade & Narayanan, 2019; Aslekar et al., 2022). Alley et al.'s (2011) observation that groundwater management is inadequate in most, if not all, countries seems to be as relevant today as earlier.

Analysis of Program Completion Reports

In addition to the empirical evidence presented above, we collected data from 33 Project Completion Reports (PCRs), which included irrigation projects implemented after 2000 by the World Bank (14 projects), International Fund for Agricultural Development (IFAD-12 projects), jointly World Bank and IFAD (3 projects), and the Millennium Challenge Corporation (MCC-4 project). There are a few indicators of project "success", including quality of infrastructure at endline and the extent to which evaluators deemed that there were major threats to sustainability versus minor threats. Most projects, with the exception of MCC projects, were evaluated just after completion, and in many cases, irrigation infrastructure was only completed near the end of the project. As Redicker et al. (2022) argue, using quality of infrastructure at endline under such circumstances is unlikely to provide evidence on the extent to which the project has met its irrigation objectives. Thus, we will focus on factors that distinguish major from minor threats to sustainability.

To compare across projects by threats to sustainability, we consider size of the irrigated area at completion, the cost of construction in USD/ha.[3], and the year the project was completed. In addition, we include a number of dummy variables that capture whether project reviewers documented specific problems in implementation that may affect threats to sustainability. These include variables that take a value of 1 if the respective document mentions project delays, procurement issues, project design problems, thin or absent markets for crop inputs and outputs and/or for goods and services to maintain irrigation infrastructure, problems related to collective action, and problems related to water scarcity. Problems related to fee payments takes a value of 1 if the document noted low rates of fee recovery, and/or that water fees are too low to cover repairs and maintenance, and/or if irrigators revenue is simply too low to cover repair and maintenance fees. Problems related to conflicts takes a value of 1 if conflicts between head and tail irrigators, tenure insecurity, or land conflicts more broadly were mentioned. Problems associated with use and enforcement of regulations takes a value of 1 if irrigation water is used by non-irrigators, if there are unregulated water withdrawals, and/or if sedimentation are mentioned as problems.

[3] We only considered costs associated with the irrigation construction, and did not include costs associated with complimentary investments such as roads.

Table 2, below, presents balance table results by a subset of irrigation scheme characteristics and problems mentioned. The second column gives the mean value for projects facing only minor threats to sustainability as identified in PCRs and the third column gives the mean value for projects with major threats identified in PCRs. The fourth column gives the standardized mean difference of the identified problem between projects considered to have minor versus major threats. We first note that 21 projects (65%) were deemed to face major threats to sustainability versus 12 projects (35%) facing minor threats. These results are consistent with Higginbottom et al. (2021) who consider that 67% of projects in their sample are deemed un-sustained. The means of irrigated area and year of completion across the threat categories are not significantly different, while costs per hectare are significantly higher for schemes facing major threats.

Table 2: Balance of Identified Project Problems for those with Major versus Minor Threats to Sustainability

	Minor Threats	Major Threats	Standardized Mean Difference	
Project Characteristics				
Irrigated Area (ha.)	8,921	12,605	3,684	
	(8465)	(35,367)	(8400)	
Costs per Ha. (USD)	5,263	11,811	6,547	*
	(4840)	(12702)	(3302)	
Year Completed	2018	2016	-1.821	
	(2.937)	(5.629)	(1.494)	
Problems Identified				
Project Delays	1.000	0.857	-0.14	*
	(0.000)	(0.359)	(0.079)	
Procurement	0.417	0.524	0.107	
	(0.515)	(0.512)	(0.185)	
Design	0.250	0.571	0.32	*
	(0.452)	(0.507)	(0.170)	
Markets	0.417	0.619	0.202	
	(0.515)	(0.498)	(0.183)	
Collective Action	0.500	0.714	0.214	
	(0.522)	(0.463)	(0.180)	
Water Scarcity	0.500	0.619	0.119	
	(0.522)	(0.498)	(0.185)	
Fees	0.333	0.714	0.38	**
	(0.492)	(0.463)	(0.173)	
Conflicts	0.583	0.524	-0.060	
	(0.515)	(0.512)	(0.185)	
Use	0.250	0.571	0.32	*
	(0.452)	(0.507)	(0.170)	
Observations	12	21	33	

Robust standard deviations in parentheses for columns 2 and 3, robust standard errors in parentheses for column 4

*** p<0.01, ** p<0.05, * p<0.1

With respect to project problems, we note that project delays are ubiquitous, and are actually higher for projects facing minor threats to sustainability. Problems with procurement and flaws in project design are higher for projects facing major threats to sustainability, with project design flaws being significantly higher. Problems associated with fees and with irrigation use regulations are also significantly higher for projects with major threats to sustainability.

Of course, we expect more problems to be identified when reviewers find major threats to sustainability, but the significant differences with our small dataset lead to some interesting hypotheses regarding the relative importance of various factors. Results suggest that irrigation scheme design and the inability to collect water user fees sufficient to ensure O&M are significantly associated with poor performance, and both are consistent with poor project preparation. Inability to collect sufficient fees is also consistent with weak institutional capacity and lack of market opportunities discussed above. Problems associated with inappropriate use and lack of collective maintenance are also likely related to weak institutional capacity. These results suggest that while there is good reason to focus on institutional capacity building particularly at the WUA level, technical issues related to design and economic issues related to irrigator profitability are also likely to be important to scheme performance and endurance as well.

Impacts on Household Livelihood Outcomes

While the focus of the paper is on the empirical evidence on the structure, functioning and performance of irrigation systems in SSA with special attention to its potential for building climate resilience, in this section we examine the evidence from SSA on the impact of irrigation investment at the household level. The ability to undertake this exercise is complicated by two factors.

First, although some studies look at multiple irrigation systems and assess the impact of these systems, many are focused on the impact of one system. Further, these studies focus on irrigation projects that, at least to a degree, are functioning since there is little benefit to evaluating the impact at the household level of a system which is clearly dysfunctional. This biases the available evidence toward single irrigation investments that have been viewed as effective.

Second, identifying impact of irrigation is complicated by concerns about selection bias. Irrigation investments are likely to be undertaken where there is agricultural potential making the areas, and households that farm there, fundamentally different from neighboring areas. Differences between those with irrigation access and those without may be due to fundamental differences between the two types

of households rather than the impact of the irrigation investment. It is hard to separate why differences emerge. While experimental and non-experimental approaches are used in some cases to identify an unbiased estimate of the impact of irrigation investment, this is not always possible and has rarely been done. Many studies have significant limitations and can only show correlation between irrigation access and outcomes and not causation. The end result is that there are few studies with reliable estimates of household level impact. We focus on those studies, which attempt to address selection issues.

With these caveats in mind, generally the evidence from SSA on single irrigation schemes indicate a positive impact of irrigation investment on farmers. In Benin, surface irrigation for rice production is associated with a 58 percent reduction in the probability of severe food security (Nonvide, 2018). In Ethiopia, the average income gains due to access to irrigation ranges from 4000 Birr to 4500 Birr per household per annum roughly doubling income compared to non-irrigator households. Among the different systems in Ethiopia, micro-dam and groundwater irrigation systems seem to have biggest effects (Gebregziabher et al, 2009). Results from Ghana indicate that irrigation has significant and positive impacts on farm incomes, employment, consumption, food security and non-farm businesses (Akudugu et al, 2021). Evidence from Rwanda show that hillside irrigation increases smallholder yields and cash profits by 70 percent (Byiringo et al, 2020). For South Africa, evidence suggests that large dams increase cropland productivity downstream, although they have a negative effect on cropland within the vicinity of the dam (Strobl and Strobl, 2011; Blanc and Strobl, 2013). Evidence from small-scale irrigation systems in South Africa also show positive effects indicating irrigator households have substantially greater per adult equivalent on consumption (more than 50 percent higher) than non-irrigator households (Sinyolo et al, 2014).

A few studies compare irrigation schemes. Evidence from Mali indicates that small-scale irrigation has a larger effect on agricultural production and agricultural income than large-scale irrigation, but large-scale irrigation has a larger effect on consumption per capita (Dillon, 2011). The results suggest that non-farm externalities and market integration may be important in realizing gains from irrigation. In South Africa, the evidence suggests that large dams have a larger impact on productivity but may be viewed as less cost-effective than small-dams. However, the evidence suggests that large dams can augment the relatively smaller positive impact of local small dams suggesting the two systems might be viewed as complementary rather than in isolation (Blanc and Strobl, 2013).

Reviews of irrigation investment also find positive effects. Looking at investment in dams, Dillon and Fishman (2019) indicate dam investments have positive impacts on productivity and income with some

evidence groundwater is better than surface water. They also show some reduction in variability in productivity as well as positive effects on poverty and expenditures. Bryan et al (2019) indicate that irrigation contributes to agricultural intensification and farm profitability and generates employment effects.

While investment in irrigation may improve outcomes among irrigators versus non-irrigators, it may exacerbate inequality if larger scale producers are able to take greater advantage of opportunities relative to small-scale producers. An analysis of six smallholder irrigation schemes in Zimbabwe, Tanzania and Mozambique finds that while poorer farmers became better-off as a result of irrigation investment, low levels of income growth led to relative inequality increases but that as growth rises beyond a certain rate there is a reduction in inequality (Manero et al, 2020). For South Africa, inequality among the poor is found to be higher for non-irrigators than it is for irrigators (Sinyolo et al, 2014) and for Ethiopia analysis points to irrigation stimulating growth without deepening inequality (Van den berg and Ruben, 2006). While it is hard to identify if irrigation causes an increase or decrease in inequality, the available evidence suggests that it depends on the context and an increase in inequality is not a forgone conclusion in irrigation investment.

The positive impact on household outcomes of irrigation investment, without exacerbating inequality, would point to a desire to invest in irrigation to improve household welfare. As noted, however, these analyses are for irrigation systems that are functioning. For South Africa, the reality of the situation is put succinctly by Sinyolo et al (2014) who conclude that even though smallholder irrigation has failed in South Africa since many schemes collapsed after government pull-out, those irrigation schemes that remain play an important role in rural poverty reduction. The key for ensuring household impact is to invest in irrigation systems that continue to function over time.

Concluding comments and policy implications

The increased interest in irrigation in SSA as a means to mitigate the threat of climate change is unsurprising. Climate change will present significant challenges to agricultural production in SSA. When irrigation systems function, the evidence points to improvements in wellbeing for those accessing irrigation and apparent reductions in variability in productivity. But the evidence also indicates that schemes in SSA have generally failed. The failure of irrigation schemes seems to stem from a host of predictable factors. Ultimately, it is a combination of technical inadequacies and management inadequacies that often stem from failures at the design stage of irrigation development. Further, systems

based on sophisticated technologies and expensive equipment can only be financially viable where irrigator profits are sufficiently high. Earlier projects tended to significantly over-estimate irrigators' adoption of cash cropping, and underestimate the importance of complimentary institutions needed to make sure profits were sufficient to cover O&M, especially for medium-scale projects (100-1000 hectares).

Without realistic designs that address both the technical and management issues, and facilitate farmer profitability, irrigation schemes are unlikely to be successful. The latter holds for irrigation investments largely assessed without considering how climate change may alter the incentives to collectively manage irrigation water resources, particularly the increasing frequency and severity of extreme weather events. Our results suggest that irrigation schemes that are not able to minimize impacts of extreme weather events on irrigation water availability are likely to face even greater problems in collecting user fees and incentivizing collective action for maintenance. There is less evidence for investments in groundwater as climate extremes increase, though evidence does suggest that incentives to invest may well increase for groundwater sources that are relatively less dependent on rainfall.

In terms of design, large-scale irrigation schemes are unlikely to avoid the "build-neglect-rebuild" cycle without compelling evidence of being financially viable, including strong support to O&M at the main and secondary infrastructure levels for activities that exhibit strong economies of scale, and the ability to allocate layers of risks across different administrative levels. The potential for conjunctive use, such as hydropower generation, to generate returns to cover infrastructure investments and operations, management, maintenance and repair costs can help alleviate fees and labor required from irrigators. These opportunities, however, are relatively limited.

Medium-scale schemes face two-fold issues: High investment and O&M costs per hectare (due to economies of scale) that are less problematic for large-scale schemes, and reliance on irrigators and their associations to meet these high costs but also successfully engage collective action to ensure fees are paid and collectively labor is provided for maintenance and repairs. The evidence indicates that medium-size schemes have limited opportunity to be successful.

The success of small-scale schemes relies on WUA performance, which is dependent on the required knowledge and skills of irrigators and WUA leadership, the extent to which WUAs manage heterogeneity of irrigators' interests, and legal recognition, amongst others. Evidence suggests that investments in small-scale schemes can be successful, when these factors are realistically considered. To ensure that irrigation

schemes of all sizes help households build resilience and achieve food security, O&M systems need to explicitly incorporate risk management mechanisms, and take advantage of the greater incentives to engage in collective action that effectively increases irrigation water reliability, which to date, seems to be absent from both designs and O&M.

Based on these considerations, the following policies are recommended for surface irrigation systems:

- Designs must incorporate climate-change related impacts under alternative scenarios and must specifically address the need to minimize volatility of water supplies, which can have large negative impacts on irrigators' incentives to engage in collective action and pay user fees unless collective action itself can increase reliability of irrigation water.
- Develop the capacity to integrate climatic data into higher-level administrative and WUA management planning, in order to harness incentives to increase reliability of irrigation water.
- More attention must be paid to achieve optimal devolution, particularly to the allocation of climatic risks – and other important risks – across different stakeholders.
- More attention must be paid to the assumptions on profitability guiding irrigation investments. In particular, assumptions on market functioning and the capacity of farmers to adopt profitable cash cropping have been excessively optimistic. Know the market! Schemes where subsistence farming will be largely practiced must make realistic assumptions on the capacity of irrigators to provide O&M and consider whether investment is merited.
- More emphasis must be devoted to "software", in particular on the knowledge and skills needed to successfully provide O&M at all relevant levels, but not at the expense of appropriate technical design and quality construction.

While surface schemes have been fraught with issues, individual investment in groundwater irrigation offers a potential path to dramatically expand access to irrigation in SSA. Farmers themselves continue to invest in groundwater irrigation, albeit at a relatively slow pace in SSA. Investment is currently hampered by the availability of cost-effective equipment and energy for pumping, as well as access to maintenance and repair service providers. As with surface scheme performance, markets for complimentary inputs and particularly for outputs are critical to fostering investment in groundwater irrigation, as are complimentary institutions.

Farmer-based groundwater irrigation avoids many of the O&M issues that beset scheme based systems in terms of payment of irrigation fees and contributions to collective maintenance. But, while over-extraction may not be a concern initially, managing groundwater extraction – an "invisible resource" – can become complex, costly and difficult, given multiple users (irrigation, domestic, and industrial) and ambiguous property rights. To ensure that groundwater irrigation supports smallholder households to increase resilience and food security now and into the future, there is an urgent need to generate knowledge on groundwater dynamics – including likely changes due to climate changes – and to develop basin-level groundwater management systems that are able to continuously monitor groundwater dynamics.

Based on these considerations, the following policies are recommended for groundwater systems:

- Knowledge on basin-level groundwater dynamics that is integrated into groundwater data systems and management platforms across multiple relevant stakeholders, from government agencies to local irrigators and their associations, and to other groundwater users is needed. This would provide a pure public good whose importance is heightened under climate change, where knowledge must be continuously updated.
- Changes in weather patterns associated with climate change, specifically lower and more erratic rainfall combined with more frequent high temperature spikes, will increase farmers' incentives to invest in groundwater irrigation where groundwater is less volatile than rainfall and off-farm opportunities are limited; however, at the basin level, this can lead to over-extraction with negative impacts on the environment and society, further bolstering the case for effective monitoring.
- Supporting farmer-led irrigation should focus on complimentary institutions that increase accessibility of irrigation equipment, access to equipment maintenance and repair services, and access to financing instruments that are attractive to smallholders.
- Much more evidence is required to understand the effectiveness of alternative irrigation technologies appropriate for smallholder use and energy sources for motorized pumps.
- To ensure that access to irrigation is equitable, land tenure and property rights over land and water are needed.

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Appendix 1: Public Goods and Common-Pool Resource Game-Theoretic Models of Risk-Averse Irrigators

The Public Goods Game:

For the public goods game, we further assume that there are two players, and that contributions to the public goods increase expected water availability and reduce yield variability. We also assume that the increase in expected water is linear public goods provision by both players, x_i, x_j.

Using the mean-variance approximation of expected utility, the players' maximization problem can be written as :

$$\max EU_{xi} = p\left[R_i + \bar{\delta}\left(x_i + x_j\right)\right] - \tfrac{1}{2}\left[R_i + \bar{\delta}\left(x_i + x_j\right)\right]\phi_i\sigma_Q^2 - cx_i \qquad [1]$$

Expected yields are given by the resource endowment, R_i, plus the increase in productivity from expected water, $\bar{\delta}\left(x_i + x_j\right)$. Expected yields are multiplied by the output price, p, minus the risk premium, where the risk premium is one half of expected yields, times the coefficient of absolute risk aversion, ϕ_i, times yield variance, σ_Q^2.

To further simplify, we set $\hat{\phi}_i = \frac{\phi_i}{2}$, and let $\sigma_Q^2 = \sigma_{\bar{Q}}^2 g\left(x_i, x_j\right)$. Here, $\sigma_{\bar{Q}}^2$ captures exogenous shocks to yield variability, and $g\left(x_i, x_j\right)$ is the "production function" that lowers yield variability. To ensure that expected utility is concave in contributions, we assume that contributions decrease variability at a decreasing rate, $g' < 0$ and $g'' > 0$.

Re-writing equation 1 and re-arranging some terms gives:

$$\max EU_{xi} = p\left[R_i + \bar{\delta}\left(x_i, x_j\right)\right]\left(1 - \hat{\phi}_i\sigma_{\bar{Q}}^2 g\left(x_i, x_j\right)\right) - cx_i \qquad [2]$$

Taking the derivative with respect to x_i, gives the following first order condition:

$$\frac{\partial EU}{\partial x_i} = p\bar{\delta}\left(1-\hat{\phi}_i\sigma_{\bar{Q}}^2 g\right) + p\left[R_i + \bar{\delta}\left(x_i, x_j\right)\right]\hat{\phi}_i\sigma_{\bar{Q}}^2 g' - c \qquad [3]$$

With the optimal x_i chosen such that:

$$\bar{\delta}\left(1-\hat{\phi}_i\sigma_{\bar{Q}}^2 g\left(x_i, x_j\right)\right) + \left[R_i + \bar{\delta}\left(x_i, x_j\right)\right]\hat{\phi}_i\sigma_{\bar{Q}}^2 g' = \frac{c}{p} \qquad [4]$$

The first term is the derivative of the expected yield function with respect to irrigation repair and maintenance contributions, and is of course increasing in those contributions. The second term captures the negative impact of contributions on water variability, increasing the marginal benefits to contributions since $g' < 0$. These are then set equal to the constant marginal cost of contributions divided by the output price to arrive at the conditionally optimal schedule of contributions, $x_i^{NC} \mid x_j$, where the superscript, *NC*, refers to the non-cooperative solution schedule. Because this is a pure public goods game, the players' reaction functions are super-imposed, and thus we can only know the total that will be provided, and not individual contributions.

Greater increases in expected water and thus expected yields unambiguously increase contributions to the public good. Thus, even under non-cooperation, we should observe greater contributions where increase expected water has higher marginal impacts on yields, e.g. in areas with more favorable soils. Higher risk aversion and greater exogenous yield variability reduce the marginal benefits to expected yields (the first term) but increase the marginal benefits to reducing yield variance. The overall impact will then be determined by which has the greater marginal impact on expected utility.

The last point is interesting in that it first appears paradoxical. Investing in irrigation is one way to adapt to climate change and the attendant increases in high temperatures and extreme weather events. However, if for example, drought events increase significantly, impacts of irrigators' actions to reduce water variability may make little difference, and incentives to provide those contributions will decline as negative impacts on expected yields dominate relatively weak impacts on water variability.

Also note that if it were not possible to reduce yield variance (if the second term is zero), then the impact of higher yield variability and/or risk aversion would be to unambiguously reduce contributions to the public good (Mason and Sandler, 1999; McCarthy et al., 2004, other cites).

Turning next to the social optimizer's maximization problem, we assume two players with homogeneous yield and variability reduction functions, the social optimizer's expected utility maximization problem can be written as:

$$EU = 2p\left[R_i + \bar{\delta}\left(2x\right)\right]\left(1 - \hat{\phi}_i \sigma_{\bar{Q}}^2 g\left(2x\right)\right) - 2cx \qquad [5]$$

Taking the derivative with respect to x gives the following first order condition:

$$\frac{\partial EU}{\partial x} = 4p\bar{\delta}\left(1 - \hat{\phi}_i \sigma_{\bar{Q}}^2 g\left(2x\right)\right) + 4p\left[R_i + \bar{\delta}\left(2x\right)\right]\hat{\phi}_i \sigma_{\bar{Q}}^2 g' - 2c \qquad [6]$$

With the optimal x chosen such that:

$$2*\left[\bar{\delta}\left(1 - \hat{\phi}_i \sigma_{\bar{Q}}^2 g\left(2x\right)\right) + \left[R_i + \bar{\delta}\left(2x\right)\hat{\phi}_i \sigma_{\bar{Q}}^2 g'\right]\right] = \frac{c}{p} \qquad [7]$$

Comparing equations [7] and [4], we see that the right-hand side is greater for equation [7] at $2x = x_1 + x_2$; in fact, it is twice the size in [7] versus [4]. This captures the fact that the social optimizer values the effect of each players contribution for both that player as well as the other player. Given that equilibrium contributions under non-cooperation and the social optimum are both equal to costs divided by output price, then the social optimizers equilibrium contribution must be greater than the non-cooperative case, as expected.

What is more interesting is to consider the case under which the gains to cooperation are greater. To the extent that collective action is costly, we expect that greater benefits to collective action would induce greater contributions to the public good (McCarthy et al., 2001). Comparing equations [7] and [4], we immediately note that the same factors that increase equilibrium public goods contributions under both non-cooperation and the social optimum will also increase incentives to cooperate, as the difference between the two solutions increases in those parameters. Thus, more profitable conditions will generate greater differences between the social optimum and non-cooperative solutions (higher output prices, lower input costs, more favorable non-weather related climate conditions). The difference between the social optimum and the non-cooperative outcomes for increases in risk aversion and exogenous variability are ambiguous, but more likely to become larger where negative impacts of risk on yields is relatively low while positive impacts of public goods on water variability are relatively high. In other words, where weather conditions are very volatile, capacity to absorb extreme weather

events is limited, and expected farm yields are relatively low, we expect the non-cooperative and social optimum solutions to differ relatively little and thus offer fewer incentives to engage in collective action.

Groundwater Extraction Game:

As with the public goods game, we add risk and risk aversion into a very simple groundwater extraction game. A dynamic game provides limited additional insight into how incentives to extract change with respect to exogenous characteristics and in determining the difference between the social optimum and non-cooperative outcomes, and so we specify a single period game, which assumes that current period extraction affects current period costs of extraction. We again assume that the farmer uses all of her resources, R_i, to farm and only chooses how much groundwater to extract. We write the farmer's expected utility maximization problem as:

$$\max EU_{xi} = p\left[R_i + \bar{\delta} k_i\right]\left(1 - \hat{\phi}_i \sigma_Q^2 - \beta * \left(k_i + k_j\right)\right) - c\left(k_i, k_j\right) \qquad [8]$$

In this case, groundwater extracted by other farmers does not have a direct impact on yields, which are now given by: $\left[R_i + \bar{\delta} k_i\right]$, where k_i is the amount extracted by farmer *i*. Since our focus is on extraction costs, we linearize the impact of extraction on water variability, $\beta * \left(k_i + k_j\right)$, which captures the extent to which extraction increases water variability. Costs are captured the function $c\left(k_i, k_j\right)$. We assume that the cost function is increasing at an increasing rate in both k_i and k_j.

Taking the derivative with respect to k_i, and re-arranging terms, gives the following first order condition:

$$\frac{\partial EU}{\partial k_i} = p\bar{\delta}\left(1 - \hat{\phi}_i \sigma_Q^2 - \beta\left(2k_i + k_j\right)\right) - pR_i\beta - c' \qquad [9]$$

With the optimal x_i chosen such that:

$$p\bar{\delta}\left(1 - \hat{\phi}_i \sigma_Q^2 - \beta\left(2k_i + k_j\right)\right) - pR_i\beta = c' \qquad [10]$$

Higher prices and higher water productivity both increase marginal yield benefits, and, since costs are assumed to increase at an increasing rate, equilibrium extraction amounts all increase with those

parameters. On the other hand, higher increases water variability due to extraction, b, greater risk aversion and higher exogenous variation all lower marginal benefits and thus reduces equilibrium extraction.

The social optimizers problem can be written as:

$$\max EU_{xi} = 2p\left[R_i + \bar{\delta}k\right]\left(1 - \hat{\phi}_i\sigma_{\bar{Q}}^2 + 2\beta k\right) - 2c\left(2k\right) \qquad [11]$$

Taking the derivative with respect to k and re-arranging terms gives the following first order condition:

$$\frac{\partial EU}{\partial k_i} = 2p\bar{\delta}\left(1 - \hat{\phi}_i\sigma_Q^2 - 4\beta k\right) - 4pR_i\beta - 4c' \qquad [12]$$

With the optimal k chosen such that:

$$\frac{1}{2}p\bar{\delta}\left(1 - \hat{\phi}_i\sigma_Q^2 - 4\beta k\right) - pR_i\beta = c' \qquad [13]$$

Clearly, the left-hand side of the social optimizers optimal k in equation [13] is lower than the non-cooperative outcome in equation [10] at the same level of $k = k_i = k_j$, capturing the fact that the social optimizer internalizes the negative externality on extraction costs and water variability that the non-cooperative individuals do not. Thus, given increasing marginal costs, extraction rates are lower at the social optimum versus the non-cooperative outcome. The difference between expected utility at the social optimum versus the non-cooperative outcome grows larger as the difference between equilibrium extraction rates increases, similar to the public goods game. This difference increases with higher output prices, higher water productivity and lower extraction externalities impacting water variability. The distance between the social optimum and the non-cooperative outcome will decrease as risk aversion and exogenous water variability increase.

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