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Impacts, maintenance and sustainability of irrigation in Rwanda

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About this report

3ie accepted the final version of the report, *Impacts, maintenance and sustainability of irrigation in Rwanda*, as partial fulfilment of requirements under grant DPW1.1085 awarded through Development Priorities Window 1. The report is technically sound and 3ie is making it available to the public in this final report version as it was received. No further work has been done.

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Summary

The following report summarizes results from the *Impacts and Sustainability of Irrigation in Rwanda* study, conducted between 2014 and 2019. The impact evaluation is a collaboration between the Ministry of Agriculture and Animal Resources in Rwanda (MINAGRI), the World Bank's Development Impact Evaluation (DIME), and the University of California – Berkeley. We examine the impacts of irrigation on smallholder welfare, through the lens of the Land Husbandry, Water Harvesting and Hillside Irrigation (LWH) project, a flagship of MINAGRI. LWH introduces sustainable land husbandry measures for hillside agriculture on selected sites and develops hillside irrigation for subsections of each site.

Irrigation investments create significant economic development opportunities for smallholder farmers who otherwise depend on rainfed agriculture, by increasing yields, adding additional cultivating seasons, and reducing risk. The key evaluation question for this study is: what are the impacts of irrigation on smallholder welfare? Specifically, we examine impacts of large-scale irrigation on yields, cropping and input choices, expenditures, labor supply and employment, land sales and rentals, migration, and whether those impacts differ by gender.

The irrigation study context consists of 4 LWH hillside irrigation schemes and their surrounding terraced land across 5 districts of Rwanda. The study is based on 4 waves of primary data collection across four years following construction of the irrigation infrastructure. We use Spatial Regression Discontinuity analysis to capture the effects of irrigation. In our baseline, collected when only a limited fraction of study sites had access to water, we find balance in household characteristics and modest relationships between irrigation and farm practices, consistent with the limited access to irrigation at that time. Our primary findings are based on the discontinuity in access to water in our follow-up surveys. Over the three years of full irrigation access in our follow-up surveys, we find that irrigation has large, positive welfare impacts for smallholders. However, adoption is inefficiently low, constrained by labor market failures.

The key results from the study are:

- **Hillside irrigation increases smallholder yields and cash profits by 70%.**
Horticultural crops are much higher value than staple crops and shifting production decisions increases returns. Dry season yields are 90% higher for plots in the command area, compared to plots outside. Profits increase by 400,000 RWF/ha (approximately \$435/ha) on irrigated plots.
- **Hillside irrigation primarily impacts dry season cultivation**
1 in 4 plots in the irrigation schemes are irrigated in the dry season, compared to only 1 in 20 plots outside the scheme. In the rainy season, irrigation usage is much lower on all plots. Access to irrigation does not increase the likelihood a plot is cultivated during the dry season; however, it does significantly shift which crops are cultivated.
- **Farmers with access to irrigation are much more likely to grow horticultural crops**
Nearly all irrigated plots are used for horticulture. In the dry season, plots in the irrigation scheme are 4 times more likely to be used for horticulture than plots

outside. In the rainy season, irrigation is nearly 2 times more likely for plots in the schemes. Horticulture replaces production of staple crops such as bananas.

- **Despite potential profitability, adoption is partial: only 1 in 4 plots are irrigated**

Moreover, adoption has not increased over time; 2-4 years after the schemes came online dry season cultivation has remained constant at about 25%. If all plots in the irrigation schemes were irrigated, welfare impacts would be 2-3 times higher.

- **Labor market failures are a key constraint to adoption**

Most households rely on their own labor for agriculture. However, horticultural production is significantly more labor-intensive than staple production. Thin labor markets present a significant barrier to wider adoption.

In the early irrigation schemes, we implement 3 randomized control trials to document the impact of complementary interventions that have the potential to increase the returns and sustainability of irrigation. The complementary RCTS answer the following questions:

1. Do self-demonstration kits increase farmers' propensity to experiment with new high-value crops and long-run use of the irrigation infrastructure?
2. What is the impact of escalating irrigation fees on farmer behavior? Will a short window of subsidized fees will induce farmers to experiment with high-value crops?
3. Does the placement of a monitor within the irrigation scheme affect resource sharing? We will measure the impact of empowering any monitor within a WUG, and of imposing that the monitor cultivates a plot in the area most likely to be harmed by overuse of water.

We do not find significant impacts from the various trials. Instead, our analysis reveals that factor markets failures, particularly thin land and labor markets, are the operative constraint for adoption of irrigation. The study shows that smaller households are less likely than large households to irrigate multiple plots, implying smaller households are not able to meet labor demands.

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Acronyms

CA	Command Area
CAC	Command Area Catchment
GoR	Government of Rwanda
IE	Impact Evaluation
LWH	Land Husbandry, Water Harvesting and Hillside Irrigation Project
MINAGRI	Rwandan Ministry of Agriculture
MINECOFIN	Rwandan Ministry of Finance
O&M	Operations and Maintenance
RCT	Randomized controlled trial
SPIU	MINAGRI's Special Project Implementation Unit
SPRD	Spatial Regression Discontinuity Analysis
SWAP	Sector Wide APproach
WUG	Water User Group
17A	Agricultural season running from September 2016 – February 2017
17B	Agricultural season running from February 2017 – June 2017
17C	Agricultural season running from June 2017 – September 2017
18A	Agricultural season running from September 2017 – February 2018
18B	Agricultural season running from February 2018 – June 2018
18C	Agricultural season running from June 2018 – September 2018

1. Introduction

The Government of Rwanda (GoR) considers agriculture an engine for the economy (cf. Rwanda Vision 2020; Rwanda's Economic Development and Poverty Reduction Strategy) and aims to reduce poverty and achieve food security through commercialized and professional agriculture. This calls for improved and sustainable productivity. The LWH is a flagship project of the Ministry of Agriculture designed to meet this objective through a modified watershed approach. It introduces sustainable land husbandry measures for hillside agriculture on selected sites and develops hillside irrigation for subsections of each site. Our study context consists of 4 such hillside irrigation schemes and their surrounding terraced land across 5 districts of Rwanda.

Irrigation investments have enormous potential to improve the lives of smallholder farmers in the Rwandan context. Rainfed irrigation in and around these sites is seasonal, with three potential seasons per year. During the main rainy season ("Rainy 1"; September - January), rainfall is sufficient for production in most years. In the second rainy season ("Rainy 2"; February - May), rainfall is sufficient in an average year but insufficient in dry years. In the dry season ("Dry"; June - August), rainfall is insufficient for agricultural production for seasonal crops. Absent irrigation, agricultural production in these sites consists of a mix of staples (primarily maize and beans) which are cultivated seasonally and primarily consumed by the cultivator, as well as perennial bananas which are sold commercially. Absent irrigation, therefore, most farmers adopt either a rotation of staples, fallowing land in the dry season, or cultivate bananas.

The research team has strong reasons to expect results from this impact evaluation program to have deep policy impacts. MINAGRI has ambitious expansion and scale-up plans for hillside irrigation: between 2014 and 17, the ministry planned to invest in 9,392 ha of hillside irrigation, accelerating in 2017/20 to 15,300 ha. Hence, the lessons learned from LWH have the potential to affect both ongoing and future investments. In addition, this study builds on DIME's ongoing program of impact evaluation with MINAGRI. As such, MINAGRI is an informed consumer of IE, and has a demonstrated commitment to using impact evaluation results to inform policy design and scale-up.

The study also has the potential for broader policy impacts, as irrigation is a priority for the region. As of 2010, only 6% of total cultivated area in Africa was irrigated; all other production was rainfed (IFPRI 2010). This impact evaluation will contribute data on the returns to hillside irrigation and lessons for scheme management, critical to informing the discussion on how to smartly invest in irrigation infrastructure to boost agricultural productivity and manage increasing climate variability. Irrigation investments are costly, and many have failed in the past to deliver the anticipated benefits. Many schemes fail for lack of collective action over basic maintenance issues, absence of a coordination mechanism to allocate water across users in the system, or for lack of adoption of a higher-value crop.

We build on a literature that studies the role of different governance structures in achieving public good provision (Alesina, Baqir, and Easterly 2000; Galliani, Gertler, and Schargrodsky 2005; Glennerster, Miguel, and Rothenberg 2013). Our contribution includes the randomized design, and the fact that we carefully measure an important, homogeneous public good with nearby natural variations in the underlying governance

structure across contiguous plots. To our knowledge, this is the first study to use a natural experiment to estimate the returns to irrigation in sub-Saharan Africa. Existing work that estimates the returns to irrigation using natural experiments is predominantly from groundwater irrigation in South Asia, leveraging variation in slope characteristics of river basins (Duflo and Pande 2007), aquifer characteristics (Sekhri 2014), or well-failures (Jacoby 2017) for identification. Estimates of the return to irrigation in Africa include Dillon (2011). While there is some evidence of the returns to irrigation in the literature (see surveys in Hussain and Hanjra 2004; Dayton-Johnson 2000; Dillon and Fishman 2019), our identification strategy relies on weaker assumptions to identify the effects of irrigation than have typically been available. Dillon and Fishman (2019) comment specifically on the scarcity of impact assessment estimates of irrigation: they note “Measuring the direct and spillover benefits and costs of dams is econometrically challenging. Impact assessments from observational data that address sources of selection bias are remarkably scarce.”

In addition, we contribute to the recent literature on technology adoption, which suggests moving away from traditional extension models and taking advantage of peer-to-peer learning and learning-by-doing (e.g. Kondylis, Mueller, and Zhu 2014; BenYishay and Mobarak 2015; Jones, Kondylis, Mobarak & Stein 2019). We provide further insights by rigorously testing self-demonstration in lieu of traditional demonstration plots.

The impact evaluation report proceeds as follows: Section 2 describes the context we study, the theory of change, and the intervention monitoring plan. Section 3 details the main evaluation questions, the study timeline, our sources of data and the model specifications. Section 4 presents the findings from the study. Section 5 provides a cost analysis, and section 6 discusses results. We conclude in Section 7.

2. Intervention

2.1 Description

We study 4 hillside irrigation schemes: Nyanza, Karongi 12, Karongi 13, and Rwamagana. Table 1 below provides details about these sites. Rainfed agriculture in and around these sites is seasonal, with three potential agricultural seasons per year. During the main rainy season (“Rainy 1”; September - January), rainfall is sufficient for all agricultural production in most years. In the second rainy season (“Rainy 2”; February - May), rainfall is sufficient in an average year but insufficient in dry years. In the dry season (“Dry”; June - August), rainfall is insufficient for production of seasonal crops. Absent irrigation, agricultural production in these sites consists of a mix of staples (primarily maize and beans), cultivated in the rainy seasons and primarily consumed by the cultivator; and bananas, which are cultivated perennially and sold commercially.¹ Absent irrigation, therefore, most farmers adopt either a rotation of staples, fallowing land in the dry season, or cultivate bananas.

¹ Staple rotations also include smaller amounts of sorghum and tubers. There is also some perennial cultivation of cassava and other minor crops. In our data, maize, beans, or bananas are the main crop for 85% of plots, excluding horticultural production.

Table 1: Canal details

	Size of full site	Size of irrigated area	Number of farmers (full site)	Number of farmers in irrigated area
Nyanza	3,051 ha	434 ha	4,965	1,300
Karongi 12	1,085 ha	142 ha	8,760	889
Karongi 13	1,335 ha	114 ha	7,012	687
Rwamagana	876 ha	215 ha	5,606	1,113

Irrigation in these schemes is expected to increase yields by reducing risk in the second rainy season and enabling cultivation in the short dry season. As the dry season is relatively short, cultivating the primary staple crops is not possible, even with irrigation, for households that cultivate during the two rainy seasons. Instead, cultivating shorter cycle horticulture during the dry season becomes a possibility with the availability of irrigation. Horticulture production (most commonly eggplant, cabbage, carrots, tomatoes, and onions) can be sold at local markets where it is both consumed locally and traded for consumption in Kigali². As horticultural production is relatively uncommon during the dry season in Rwanda due to limited availability of irrigation, finding buyers for these crops is relatively easy during this time. Prior to the introduction of irrigation, horticulture is known but uncommon in these areas; at baseline 3.2% of plots outside of the command area are planted with any horticulture, primarily during the rainy seasons.

Construction of the schemes we study was completed in 2014 for the first 3 sites and in 2018 for the last site (Rwamagana). The study period includes 4 years after the sites became operational in the first 3 sites, and 1 year in the last site. This allows us to look at adoption dynamics over time as well as maintenance issues.

The schemes in our study share common features; Figure 1 provides a visual illustration of the command area and command area catchment in one of the sites. In each site, land was terraced in preparation for the irrigation works (as hillside irrigation would be infeasible on non-terraced land). Construction and rehabilitation of terraces in these sites began in 2009 – 2010 (2016 for Rwamagana). The schemes are all gravity fed and use surface water as the source³. From these water sources, a main canal (visible in Figure 1) was constructed along a contour of the hillside; engineering specifications required the canal to be sufficiently steep so as to allow water to flow, but sufficiently gradual to control the speed of the flow, preventing manipulation of the path of the canal. The first, small stretch of the main canal was existing but significantly rehabilitated and expanded under the project. In the majority of the irrigation scheme, the main canal is newly constructed and there was no existing canal system.

Secondary pipes run underground below the terraces, these pipes are placed every 200 meters along the primary canal. Farmers draw water from tertiary valves which are located on every third terrace. From these valves, flexible hoses and dug furrows enable irrigation on the plots. Working on the terraces, farmers dig (temporary) tertiary canals in the soil to draw the water from the flexible pipe and irrigate the terrace. In general,

² Kigali is less than a 3-hour drive from these markets, facilitating trade

³ In two sites, a river provides the water source, while in the other two sites, a dammed lake is the source

households will own plots on multiple terraces and multiple households will own plots on the same terrace being irrigated by the tertiary canal, so that this exercise relies upon terrace-level cooperation. Farmers are responsible for maintaining the dug furrows and using the hoses to apply water from the valves to their plots.

The “command area” for the schemes, the land that receives access to irrigation, includes all plots below the canal and located within 100 meters of one of the tertiary valves. In all sites, sufficient water is available to enable irrigation year-round. To the extent that there is heterogeneity in plot-level water pressure, the plots nearest to the canal face the lowest pressure. The lower pressure on these plots is attributable to the design of the pipes, which fill up with water before valves are opened; forces of gravity and the lower volume of water in the pipes above the highest valves generates somewhat weaker pressure than at the lower valves (though pressure is still sufficient for effective irrigation). This difference in pressure could become more serious if lower valves were opened at the same time as higher valves; in practice, schedules of water usage are agreed upon to prevent this from happening.

Figure 1: An image of the Karongi 12 site



Note: Source - Jeremy Magruder, 2015

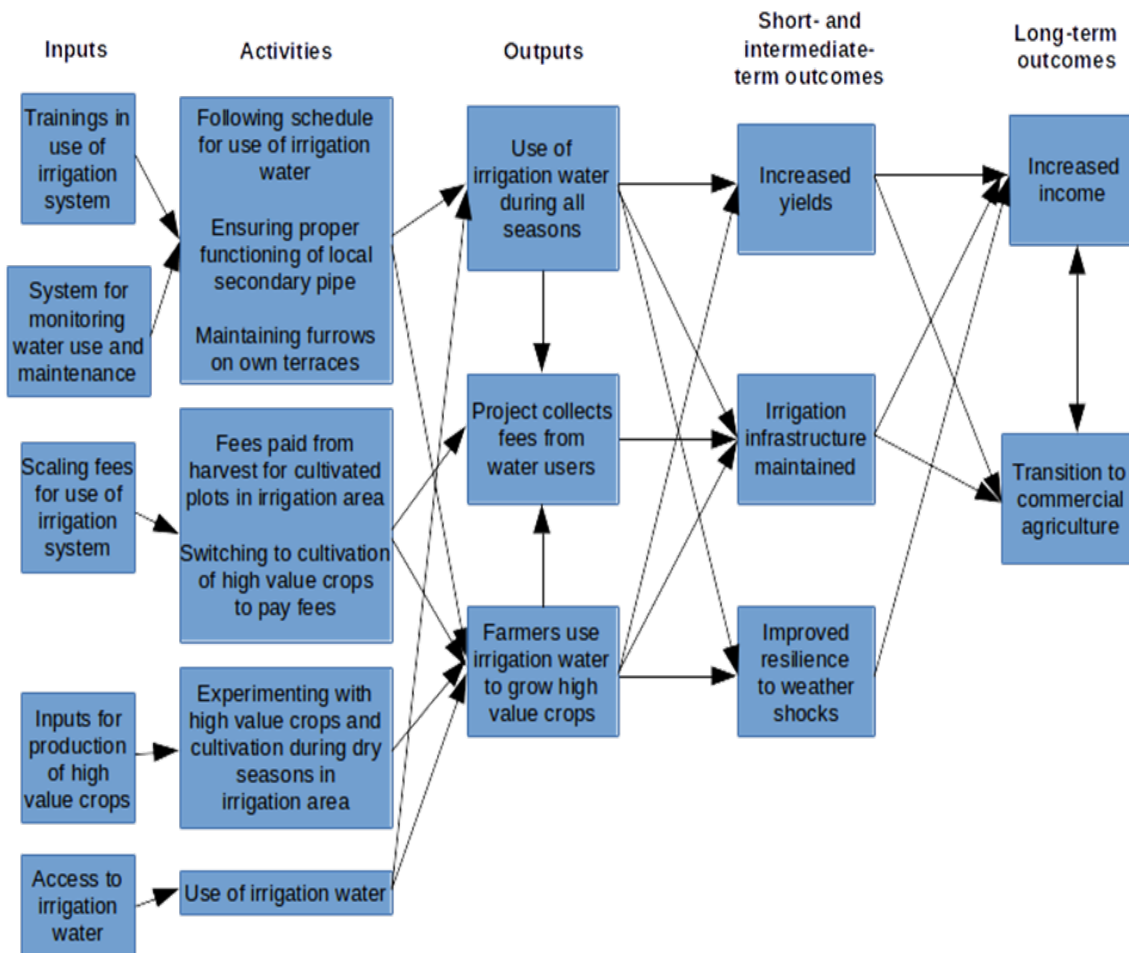
Water User Groups (WUGs) are formed at the secondary pipe level. Groups of approximately 20 households (range of 5- 50 at baseline; median of 19) rely on the same secondary canal to irrigate their terraces. WUGs are responsible for the maintenance of the secondary canals and tertiary pipes, and the scheduling of water use within their block.

Water user fees are designed to cover maintenance of the scheme, rather than full cost-recovery. All farmers that cultivate plots in the command area are expected to pay usage fees. Fees are approximately 40,000 RWF/hectare-season (about \$52 per hectare per season; the average farmer cultivates about 0.3 hectare within the scheme) when all costs are included. This level of fee is sustainable with high-value crop production, such as horticulture, but not with staple crops.

2.2 Theory of Change

Figure 2 below presents a simplified theory of change behind the interventions to be evaluated, including its main components/inputs, activities, outputs, and the hypothesized causal chain to select outcomes of interest.

Figure 2: Theory of change



The theory of change is that irrigation access and experimentation with high-value crops create a virtuous cycle: productivity improves as farmers learn how to cultivate high-value crops; farmers use the irrigation system, and pay the requisite water user fee, because it is necessary for cultivation of high-value crops; and farmers properly use and maintain the irrigation system because their profitable production becomes dependent on it. Additionally, this constant use of the irrigation system allows LWH to collect enough fees to make the irrigation scheme sustainable.

In the study area, the relevant high-value crops are horticultural crops, most commonly eggplant, cabbage, carrots, tomatoes, and onions. These can be sold at local markets; they are both consumed locally and traded for consumption in Kigali. Horticultural crops have a sufficiently short cropping cycle to allow for cultivation in the relatively short “Dry” season, unlike staple crops.

There are two main assumptions behind the theory of change.

First, we postulate that farmers cannot afford the water usage fees (which cover the costs of maintaining the infrastructure) while cultivating traditional crops but can while cultivating high-value crops, such as horticulture. This is confirmed both by numbers from a crop model used by our partner organization, LWH, and in data from our baseline, in which observed horticultural revenue per hectare is double or more revenue from traditional crops. Access to irrigation infrastructure enables off-season cultivation of high-value crops and reduces the yield risk associated with cultivating high-value crops the rest of the year. At baseline, very few of the sampled farmers used any type of irrigation on any of their plots, and as a result few commercially cultivate high-value crops. Farmers may not experiment with adoption of high-value crops if the gains from adoption are not clear. Compared to staple crop production, horticulture is more input-intensive and requires more market access. If access to inputs is a binding constraint to initial experimentation with horticulture; reducing that constraint could catalyze the virtuous cycle of high-value production and irrigation described in the main theory of change.

Second, we assume that the irrigation infrastructure cannot add value unless farmers coordinate both their usage of the irrigation water (operations) and contribute to maintaining the public good, while adopting high-value crops. WUGs have been organized to monitor and coordinate O&M. O&M will not occur in the absence of a switch to high-value crops, as irrigation does not add value in cultivation of traditional crops in the irrigation sites we study. Moreover, even under adoption of high-value crops, incentives to coordinate vary within the water user group. Farmers with tertiary valves near the bottom of their secondary pipe can use water even when other farmers are using their tertiary valves, while the reverse is not true, and as a result, farmers near the bottom have no private incentive to coordinate operations. For instance, farmers with plots furthest from the secondary pipe need the furrows which carry water from the tertiary valves to their plot to be properly maintained, or else they cannot use the water.

Within 3 of the 4 irrigation schemes, we ran three experiments that target these causal pathways at the inputs stage. First, we give some farmers agricultural minikits to experiment with high-value horticultural crops. These minikits include small quantities of inputs for cultivation of high-value crops on a small plot of land. Additionally, we provide them to farmers before the off season, enabling low-cost experimentation with cultivating high-value crops using the irrigation infrastructure in the newly added season. Second, we vary the season in which farmers begin to pay water usage fees, delaying the first season of payments one or two seasons for some farmers. Third, we randomize how monitors are chosen within water user group and whether these monitors have incentives to ensure optimal operations and maintenance activities. The monitor are either an employee of LWH, appointed by the water user group, or appointed by the water user group with the spot reserved for a farmer with plots near the top of their secondary pipe (the farmers near the top are most negatively impacted by over-use of water).

We can now fit these interventions into the theory of change. Agricultural minikits reduce the cost of experimentation with high-value crops. Experimentation and eventually cultivation at scale of high-value crops is only possible while the irrigation system is properly maintained and used, since the high-value crops are more dependent on access to water than traditional crops. Delaying implementation of fees reduces the riskiness of experimentation, but also weakens the push for farmers to adopt high-value

crops. Common-pool resources are subject to overuse; farmers who are most negatively impacted by collective action failures may be the most effective monitors. By targeting all these barriers to adoption simultaneously, we can move households in the irrigation schemes into a new equilibrium where the irrigation infrastructure is actively used to cultivate high-value crops year-round, significantly increasing profits for these households.

2.3 Intervention monitoring plan

2.3.1 Monitoring RCT implementation and compliance

Minikits experiment: Mini-kits were allocated through a lottery in the field, which was monitored by representatives from the research team. From January-February 2017, we conducted an on-farm monitoring survey among the treated households of the demonstration kits intervention, to collect data on the experience with the horticultural crop included in the mini-kit. Our sample was composed of 427 households (number of households that collected the mini-kit), and we managed to interview 391, or a response rate of 91.57%. We confirmed that the household received the mini-kit, what was included in the package, and whether the seeds were planted and, if not, the reason why.

Subsidies experiment: Water fee subsidies were allocated through a lottery in the field, which was monitored by representatives from the research team. Farmers received cards with water fee subsidy results; these were photographed during the follow-up survey as a check. During each season, LWH staff worked with the WUGs to measure and document cultivated area, to assess water user fees. We monitored the repayment of the water user fees by farmers, with the help of the WUA managers. The WUA managers had sheets with lists of farmers in each WUG, area of land, and the amount of fees they have to pay for each season. They filled in the fee information whenever they visited the farmers to collect the fees. We helped the WUA managers by printing invoices depending on the lottery type and the WUA managers provided us receipts for each payment.

O&M experiment: we worked jointly with LWH staff to develop Operations and Maintenance trainings, which were implemented through a ToT model to all farmers at the Water User Group (WUG) level. Details of the training are provided in Appendix C. Farmers were instructed on the purpose of the WUGs, and trainers collected details of WUG members. Farmers selected their Monitor, and the name of the Monitor was recorded. We monitored the training of trainers and training of farmers closely to make sure the materials were taught as planned and that monitors were elected according to the study protocols. We monitored ongoing adherence to the treatment by entering and reviewing the data from the monitors' weekly worksheets, which were collected regularly through the Water User Group. In case submissions were not made on time, there was a follow-up to the Monitor to make sure that s/he was still performing his/her duties. In a few cases, the Monitor resigned partway through and was replaced with a new WUG member, who was trained by LWH staff. In the household surveys, we confirmed the identity of the WUG monitor as applicable.

2.3.2 Monitoring data quality

All quantitative data collection was done by Innovations for Poverty Action (IPA). To ensure quality, data checks were run daily, and the monitoring activity was scheduled and designed such that each surveyor was observed, spot checked or back checked at minimum, once a week. The different quality control measures put in place during the baseline are listed below.

- o *High frequency checks*: data checks were run daily to gather information regarding quality of the data, enumerator performance, programming errors in the digital data collection program, and any systemic flaws in the data flow. Any errors identified were rectified daily.
- o *Accompaniments (random)*: To better check the survey quality, a minimum of 10% of respondents surveyed by each surveyor were observed. This was done through random field visit to enumerators in different households.
- o *Spot check survey (random)*: Spot checks (surveys which a supervisor completes while observing an enumerator) were implemented to help monitor enumerators and verify the enumerator is following the survey protocols. In the first two weeks, most of the enumerators were visited. The monitoring activity was scheduled and designed so that each surveyor was observed at minimum, once a week.
- o *Back check survey*: A back check survey consisting of a bare minimum of 10 questions were asked for 15% of the sample. This was used as a method of monitoring and auditing data quality. If differences occurred on comparison with the main survey, households were revisited, and corrections were made where necessary.

3. Evaluation questions, design, methods, sampling and data collection

3.1 Primary and secondary evaluation questions

There are four primary research questions being addressed by the study:

1. What are the impacts of irrigation on smallholder welfare? Specifically, we will examine impacts of large-scale irrigation on yields, cropping and input choices, expenditures, labor supply and employment, land sales and rentals, migration, and whether those impacts differ by gender.
2. *Minikits experiment*: Do self-demonstration kits encourage experimentation and long-run adoption? If so, how does this interact with water usage fees? We hypothesize that farmers who receive minikits will be more likely to experiment with high-value crops, and that effects will be larger when water usage fees are higher. Moreover, we hypothesize that farmers who experiment will be more likely to continue using the irrigated land when charged full water usage fees in the future.
3. *Subsidies experiment*: What is the impact of escalating irrigation fees on farmer behavior? In the long-run, farmers will have to pay substantial fees. Fees will outweigh benefits if farmers continue to produce low-value crops; therefore, for sustainability, farmers will have to either adopt high-value crops or reallocate land (through sales or rental). We hypothesize that a short window of subsidized fees will induce farmers to experiment with high-value crops.

4. *O&M experiment*: Does the placement of a monitor within the irrigation scheme affect resource sharing? A key dimension of heterogeneity in irrigation schemes relates to plot location: people living near the main canal will have different incentives to maintain the secondary and tertiary canals than those who live far from it. They will also have different incentives to (over)use water. We will measure the impact of empowering a monitor within a WUG, and of imposing that the monitor cultivates a plot in the area most likely to be harmed by overuse of the resource.

3.2 Evaluation design and methods

3.2.1 Impacts of Irrigation

We exploit a spatial discontinuity in irrigation coverage to estimate the impacts of irrigation. Because the main canals must conform to prescribed slopes relative to a distant and originally inaccessible water source, the geologic accident of altitude relative to this source determines which plots will and will not receive access to irrigation water. Hence, before construction, plots just above the canal should be similar to plots just below the canal, and importantly, should be managed by similar farmers. Following construction, however, the plots just below the canal fall inside the command area and have access to irrigation, while the terraces just above the canal fall outside the command area and do not have access to irrigation.

3.2.2 Minikits experiment

We give some farmers agricultural minikits to experiment with high-value horticultural crops. These minikits include small quantities of inputs for cultivation of high-value crops on a small plot of land. We will provide the minikits to farmers before the Dry season, enabling low-cost experimentation with cultivating high-value crops using the irrigation infrastructure. The agricultural minikits are small packages containing seeds for horticultural crops (see table below for quantities), compost (200 Kg), chemical fertilizer, and pesticides sufficient to cultivate a plot of 2 ares.⁴ shows the composition of agricultural minikits provided.

Table 2: Composition of agricultural minikits

Crop	Quantity of Seeds
Carrot	60 gr
Onion	60 gr
Eggplant	50 gr
French bean	500 gr / 1.7 kg
Garlic	7 gr
Tomato	10 gr
Watermelon	25 gr

Random assignment of minikits was done at the household level, with crops allocated by zone. Farmers who were offered the minikit chose if they wanted to use it. To use it, farmers had to prepare the land to plant the crop included in their minikit; they were

⁴ Are, a common unit of measurement in Rwanda, is equivalent to 0.01 hectares.

assisted by horticulturists during this process. The district agronomists provided extension advice during the season.⁵

The intervention took place in two seasons, Season 17A and Season 17C. It was initially supposed to take place in season 17A only, but due to delays with procurement of inputs, farmers faced production challenges. Hence, we decided to repeat the intervention during season 17C, to be able to provide the farmers with all the inputs at the right time.

During season 17A, treated farmers were offered a minikit that included seed and compost. During season 17C, farmers that had collected the minikit during 17A were offered a second package, which included seeds, compost, fertilizer, and pesticide.

3.2.3 Subsidies experiment

Our experiment randomly allocated subsidies to different farmers. Since learning may take more than one season for full results, we randomized a path of subsidies over two seasons. Fees were around 40,000 RWF/hectare-season (about \$52 per hectare; the average farmer cultivates about 0.3 hectare within the scheme) with costs are included; this level of fees was to be collected from all cultivating plots. After discussing the eventual fee with farmers, they took part in a lottery to pay according to one of four schedules as detailed in Table 3.

Table 3: Fee schedules

Option	2016 Season C Fee (RWF/hectare)	2017 Season A Fee (RWF/hectare)	2017 Season B/C Fee (RWF/hectare)	Approximate Number Farmers
1	0	0	40000	300
2	0	20000	40000	300
3	0	40000	40000	300
4	40000	40000	40000	800

We vary the season in which farmers begin to pay water usage fees, delaying the first season of payments one or two seasons for some farmers. The first season in which water usage fees were charged was season 17A (September 2016 – February 2017). Prior to this season, a lottery was conducted to allocate subsidies for both Season A and Season B Fees. At the lottery, farmers received cards they could keep with the outcome of the lottery; the template for the card is provided in Appendix D.

3.2.4 O&M Experiment

We use a Randomized Control Trial (RCT) to test the optimal monitoring structure. The randomization determines which member is empowered as a monitor within a Water User Group. In 76 random WUGs, the WUG will elect a monitor from its members. In another 76 random WUGs, the WUG will elect a monitor, but the position will be reserved for a farmer who cultivates land close to the main canal. Counterintuitively, these are the farmers most exposed to collective action problems in our context, since

⁵ Control households also had access to the zone horticulturalist. Hence the treatment effect we estimate is the additional effect of minikits, and not the combination of minikits and extension advice.

they cannot draw water while farmers below them are using the water. The remaining 100 groups will continue to have an employee of LWH monitoring their water use.

We randomize how monitors are chosen within water user group and whether these monitors have incentives to ensure optimal operations and maintenance activities. The monitor will either be an employee of LWH, appointed by the water user group, or appointed by the water user group with the spot reserved for a farmer with plots near the top of their secondary pipe (the farmers who are most negatively impacted by collective action failures). Across treatment arms, a subset of monitors will be paid based on how often water flows from the tertiary valves on their secondary pipes at the scheduled times.

A series of training were organized to introduce farmers to the irrigation schemes and to key organizations and staff. Trainings were done at the WUG level. WUGs assigned to the monitoring treatments elected their monitors during the training.

Monitors were tasked with completing simple worksheets on function of the irrigation infrastructure for their group on a weekly basis. First, monitors were asked to mark the days in which there was irrigation in their block, or to leave it blank if there was no irrigation at all. Second, they were asked to indicate whether any of a list of possible maintenance events had occurred. The list included 11 events, related to routine maintenance and water sharing.

3.2.5 Overlap of samples across interventions

Table 4 below details the overlap of households across each treatment arm.

Table 4: Overlap of samples across interventions

Treatment combinations				No of HHs
RD Treatment	No minikits	No subsidies	No O&M	780
RD Treatment	No minikits	No subsidies	Received O&M	212
RD Treatment	No minikits	Received subsidies	Received O&M	86
RD Treatment	Received minikits	No subsidies	Received O&M	40
RD Treatment	Received minikits	Received subsidies	Received O&M	291
RD Control	No minikits	No subsidies	No O&M	477
RD Control	No minikits	No subsidies	Received O&M	99
RD Control	No minikits	Received subsidies	Received O&M	47
RD Control	Received minikits	No subsidies	Received O&M	3
RD Control	Received minikits	Received subsidies	Received O&M	151

3.3 Power calculations

Power calculations as presented in the initial proposal used baseline data (the baseline of this project was funded from a separate source) and therefore have not changed. Here, we show the addition of a fourth irrigation scheme, which boosts power for measuring the overall impact of access to irrigation. Note that we do not have to update the power calculations for the other interventions as no other interventions were implemented in the fourth site. To quantify, using the same assumptions submitted along with the proposal, addition of the households from the Rwamagana site (340 below the

primary canal and 359 above) to the initial sample, the MDES now is between 0.11 – 0.13 (depending on the assumed level of autocorrelation), as shown in Table 4 below. The outcome variable of interest for the power calculations is agricultural yields measured in Rwandan Francs per hectare.

Table 5: Power calculations

Parameter	Test 1: high autocorrelation	Test 2: medium autocorrelation	Definition
α	0.05	0.05	Significance level
β	0.8	0.8	Desired power of the test
Tail	2	2	One-tailed or two-tailed test
μ	12761	12761	Pooled mean of outcome variable (yield in RWF/ha)
σ_y	24233	24233	Pooled standard deviation of outcome variable (yield in RWF/ha)
P	0.52	0.52	The proportion of the study sample randomly assigned to treatment
n	690	690	The size of the study sample
pre	1.00	1.00	Number of baseline measurements
post	2.00	2.00	Number of follow-up measurements
ρ	0.75	0.50	Correlation between baseline and follow-up measurements
stata code	<i>sampsi 12761 15930, sd1(24233) method(change) pre(1) post(2) n1(359) n2(331) r1(.75)</i>	<i>sampsi 12761 17240, sd1(24233) method(change) pre(1) post(2) n1(359) n2(331) r1(.5)</i>	stata package: sampsi
δ	0.13	0.18	Minimum detectable effect (in standard deviations)

Please refer to the spreadsheet in Appendix E for additional details on the calculations, including software package used and all assumptions.

3.4 Follow up qualitative work

We used qualitative research as a follow up to the data collection to be able to supplement the findings from the evaluation and better understand reasons for unanswered questions from the quantitative research. We employed focused group discussions as the main tool to understand reasons for low irrigation take up; a focus group discussion outline was developed for this. While the FGD guide was left flexible to have a free-flowing conversation, challenges to irrigation adoption and potential solutions to optimize irrigation adoption was the central theme.

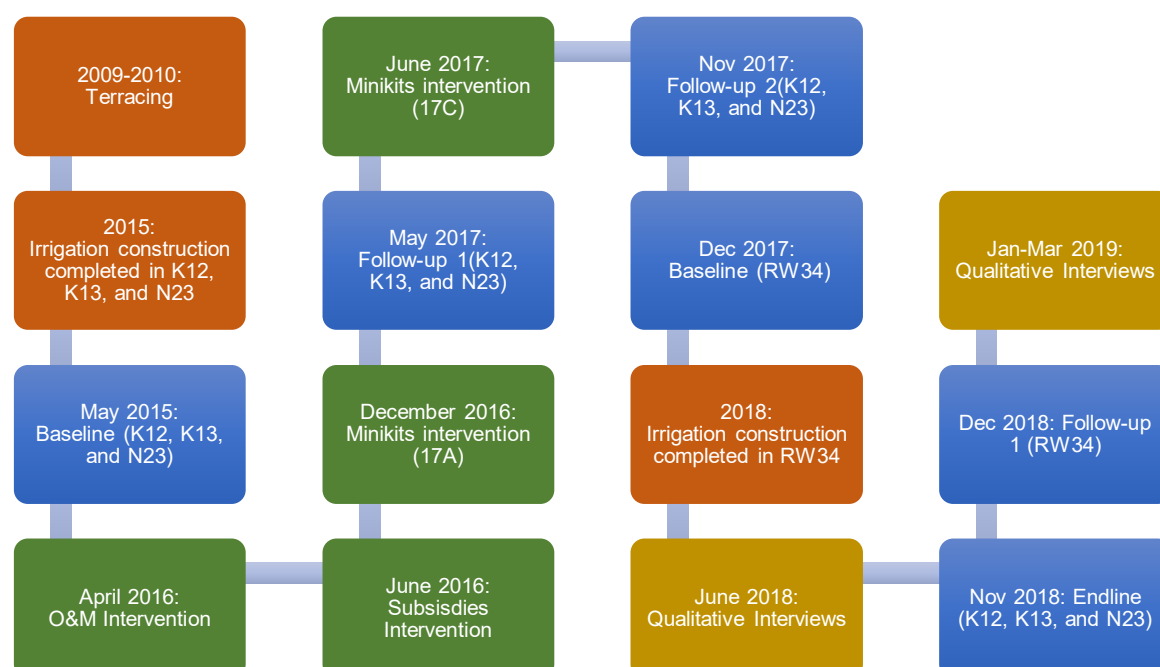
Three (3) Focus Group Discussions (FGD) were conducted in one of the four sites (Karongi 13). We first held a focus group discussion with 6 village leaders and 2 Water User Association committee members, followed by another two FGDs with 35

participants from two randomly selected Water User Groups. Through these discussions, we navigated through understanding farmers agriculture practices to set the tone of the conversation. Extensive notes were kept by the team conducting the FGDs and the major learnings from these were used to motivate the discussion around the findings from the evaluation.

3.5 Timeline

Figure 3 below provides a pictorial representation of the timeline for our data collection alongside the project implementation. Please note that each wave of survey data collection included a year of retrospective agricultural data. Although the baseline survey took place when the scheme construction was finalizing in the first 3 sites, as it was retrospective, the seasons covered in the survey were not affected by the new infrastructure.

Figure 3: Study Timeline



3.6 Ethics

The research team applied for and received ethical clearance from the Human Subjects Committee for Innovations for Poverty Action IRB, UC-Berkeley, and the Rwanda National Ethics Committee. A survey visa from the Rwandan National Institute of Statistics was also applied for and received.

We anticipate no major risks to participants in the study - treatments all involve no gifts or unforeseen benefits; we took all possible precautions to guarantee that subject data is kept confidential, and subjects were reassured that they have the prerogative to exit the study without loss of benefits.

The study is registered with the AEA RCT registry with the title '*Technology Adoption and Public Good Provision: Evidence from Hillside Irrigation in Rwanda*'. The registered study can be found [here](#).

3.7 Sampling and data collection

3.7.1 Sample selection

For three of the sites that are being used for the spatial regression discontinuity analysis (K12, N23, and R34), we divided the site into 3 areas – CA buffer (BCA), CA Catchment buffer (BCAC), and CA terraces (TCA). BCA is the area inside of the CA (CA, below main canal) within 50m of the boundary of the CA. BCAC is the area in the CA Catchment (CAC, above main canal) within 50m of the boundary of the CA. TCA is the terraced farmland that is in the CA, but more than 50m from the boundary of the CA. The third site will be used for the within-CA experimental designs only, and as a result we focused our sampling in one area – the CA terraces (TCA).

We constructed our household sampling by dropping a uniform grid of points across the full site at 2-meter resolution, and then sampling points within the grid. After each point was sampled, we excluded any points within 10m of that point (to keep from selecting multiple points too close together).

Enumerators were then given GPS devices with the locations of the points, and sent to each point, with a key informant (often the village leader). For each point, they were asked to identify if the point was on cultivable land (this was to discard forest, swamps, thick bushes, bodies of water, or other terrain which would make cultivation impossible). They were asked to record, for points in cultivable land, in SurveyCTO, the following:

1. The name of the point visited (which was displayed on the GPS);
2. The name of the cultivator, the location of their residence, and their phone number;
3. A description of the plot detailed enough that the cultivator would be able to identify the exact plot described

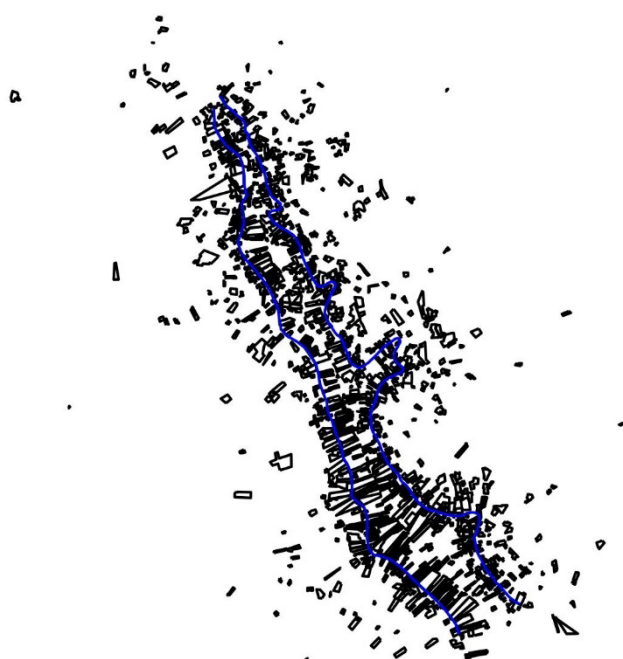
Additionally, they were asked to save their GPS track at the end of the day, as a way of tracking the number of hours they spent checking points and to verify that they visited each point. We used the data from this listing to construct a roster of all the unique names of cultivators, clustering points together when the names seemed identical. This roster (which contained the name of the individual, their village and phone number, the descriptions of the plots, and the villages in which the plots were located (identified using village shapefiles) and were organized by village) were then used to contact village leaders and verify that the listed individuals in fact existed. Multiple follow-ups were sometimes needed when village leaders suggested that one individual lived in a different village, or multiple village leaders said an individual lived in their village.

Finally, a sample plot was selected for each verified 2689 households. To select this sample plot, one point was randomly selected for each household. The probability of selecting a particular point was weighted – a weight of 1 was assigned to points in the BCA and BCAC, and a different weight was assigned for points in the TCA, to balance the number of sample plots in these areas (see Table 5 for the full list, and Figure 4 for an illustration of the geographic relationship between the sample plots and the canal).

Table 6: Distribution of sample plots

Site	Sampled Households	Area	Sampling Weight	# Sample Plots
N23	877	BCA	1	323
		BCAC	1	362
		TCA	2	192
K12	593	BCA	1	185
		BCAC	1	211
		TCA	0.25	197
K13	409	TCA	--	409
RW34	810	BCA+BCAC	1	810

Figure 4: Sample plots in relation to irrigation canal



Source: Mapping of geo-coordinates of canal and sample plot collected by the team

The baseline in K12, K13, and N23 was conducted in May 2015. There were 3 follow up household surveys conducted in K12, K13, and N23. The first one took place in May and June 2017, the second one took place in November and December 2017, and the third took place in November and December 2018. For RW34, the baseline household survey was conducted in January 2018 and the first follow up was conducted in December 2018. All were panel surveys, including the same set of respondents.

3.7.2 Data description

The questionnaire was structured such that agricultural data is collected plot-by-plot, for each agricultural season. The plots were identified with plot descriptions (from the farmer) and geo-tags, to construct a plot-level panel. The survey was answered by the decision makers in the household. Table 6 lists the survey modules. Table 7 lists outcomes of interest. The complete instruments have been attached as a supporting document.

Table 7: Baseline survey modules

Module	Content	Level
Identification	Identification of enumerator and respondent; informed consent	Household
Household Roster	Sex, age, education, employment, migration	Household member
Plot Roster	Plot identification, ownership status, cultivation by season, past land transactions	Plot
Crop Production	Crops produced (cash vs. subsistence), amount of seed, amount harvested, amount consume, amount sold, amount lost to spoilage	Crop (by Plot and by Season)
Use of Irrigation	Use of irrigation, source, method, frequency	Sample plot
Farm Labor	Use of household and hired labor for agriculture	By plot and by season
Agricultural Inputs	Quantity, source, and amount spent on all organic and chemical inputs	By plot and by season
Irrigation (general)	Experience with irrigation, knowledge of maintenance, participation in maintenance activities, participation in trainings	Household
Extension	Interaction with public, private, and not-for-profit sources of agricultural extension	Household, by season
Housing	Construction material of walls and floors, source of drinking water, sanitation	Household
Farmer Group	Participation in farmer group, cooperative, water user group, and water user association	Household
Social Networks	Interactions, transfers to/from, and loans to/from, community work with neighbors and members of water user groups	
Income & Expenditures	Disaggregated income over the past 1 year; access to market; disaggregated expenditures over the past 1 month (frequent categories like communications and transportation); disaggregated expenditures over the past 1 year (infrequent categories like school fees and health insurance)	Household
Animals & Assets	Total owned; sales and purchases over the past one year for: cows, goats, pigs, poultry, radios, mobile phones, furniture, bicycles, hoes and shovels, and other agricultural equipment	Household
Rural Finance	Bank accounts; formal savings; contributions to ROSCAs	Household
Credit	Number of loans requested; amount and purpose of loans received	Household
Shocks	Crop failure in the past year associated with drought; amount of loss and means of coping	Household, by season
Future Expectations	Future expectations and perceptions of agricultural production, household wellbeing, impacts of irrigation, asset purchases, participation in contract farming	Household
Food Security	Food Consumption Score (developed by World Food Program)	Household
Plot mapping	Map of two plots of interest: Sample plot and most important plot	Household

Table 8: Indicators of interest

Outcome Type	Outcome Name	Definition	Measurement Level
Primary	Gross Agricultural Yield	Total value of output per hectare	Agricultural plot
Primary	Net Agricultural Yield	Total value of output per hectare minus total value of inputs (including labor) per hectare	Agricultural plot
Primary	Expenditures	Household expenditures in the past month (frequent) and year (infrequent)	Household
Secondary	Adoption of high-value crops	Choice of crop(s) cultivated, per season	Agricultural plot
Secondary	Payment of water-usage fee	Amount paid as a proportion of the amount owed (given subsidy)	Agricultural plot
Primary	Primary employment	Primary source of employment, self-reported	Household member
Primary	Land sales and rentals	Land sales over the past 5 years; ownership status and decision to rent out or in by plot	Agricultural plot
Primary	Migration	Dummy for whether the HH member migrated for work during the reference period	Household member
Primary	Maintenance of irrigation scheme	Score based on objective measures of level / quality of maintenance performed, directly observed through monitoring	Tertiary Valve

Extensive qualitative data was conducted in mid-2018 and led by Christophe Ndahimana, a local researcher. Focus group discussions were conducted with water user groups in Karongi to unpack the findings from the quantitative surveys. Details of the qualitative work done are explained in Section 4.

3.7.3 Secondary survey and administrative data

LWH staff collected data on payment of water user fees from the Water User Groups which we use to corroborate the self-reports of fees payment made.

3.8 Specifications

3.8.1 Impacts of Irrigation

To estimate the impacts of irrigation, we make use of the fact that the position of the main canals is largely proscribed by engineering specifications: in a hillside context like Rwanda, canal water must flow within a narrow range of slopes along a contour of the hillside. Thus, the canal was constructed without consideration for the characteristics of specific plots, and presumably there are very similar plots just above and just below the canal.

For this report, we focus on a simple boundary discontinuity specification; our identifying assumption is that for plots within 50m of the boundary of the command area, it is as good as random whether the plot is inside the command area (and has access to irrigation) or is outside the command area (and does not have access to irrigation). We therefore estimate:

$$y_{ist} = \beta_0 + \beta_1 CA_{is} + \alpha_{st} + \epsilon_{ist}$$

Where y_{ist} is outcome y of household i located in site s in season t , CA_{is} is an indicator for the household's sample plot being in the command area, and α_{st} are site-by-season fixed effects meant to control for any differences or trend differences across sites (including market access or prices). To interpret these site-by-season fixed effects, note that this regression is equivalent to estimating this regression (without the fixed effect) separately for each site in each season, and then averaging across the estimated effects from each site in each season. To ensure that our plots are representative, these sample plots that we focus on are the plots we randomly selected through an aerial sampling procedure, described above.

3.8.2 Minikits experiment

We estimate the impact of minikits using the specification

$$y_{ist} = \beta_0 + \beta_1 \text{Assigned minikit}_i + \beta_2 \text{Minikit saturation}_i + X'_{ist} \gamma + \epsilon_{1ist}$$

Assigned minikit_i is a dummy for whether household i was randomly assigned to receive a minikit, *Minikit saturation_i* is the probability of receiving a minikit for households in the water user group of household i sample plot, and X_{1is} includes the stratification variables (Zone fixed effects and O&M treatment status), as well as indicator variables reflecting the probability that a household would receive a minikit⁶ and in some specifications 2016 Dry horticulture adoption. As minikit saturation is assigned at the water user groups level, robust standard errors are clustered at the water user group level.

3.8.3 Subsidies experiment

We estimate the treatment effects for subsidies using T-C comparison after stratifying on covariates using the regression form listed below.

$$y_{ist} = \beta_0 + \beta_{1S} T_{is}^S + X'_{ist} \gamma + \epsilon_{ist}$$

where $T_i^S = 1$ if farmer i in site s receives subsidy of type S in season t , and X_{ist} are stratifying covariates.

3.8.4 O&M experiment

For the treatments on O&M, since treatment is randomly assigned, we can simply estimate

$$y_{it} = \beta_0 + \beta_1 T_{is} + X'_{ist} \gamma + \epsilon_{ist}$$

Where T_i indicates the treatment status of household i in site s and other variables are defined as before. For O&M specifications, we include in X_{ist} all stratifying variables and cluster at the WUG level.

⁶ After matching names from the lists of water user group members to our baseline survey, we found that 32% of households either had multiple household members on the lists of water user group members or had a single household member listed multiple times; these households are more likely to be assigned to receive a minikit and may differ from other households

4. Findings

4.1 Intervention implementation fidelity

For the sites of Karongi and Nyanza, we saw 5.3% (90/1695) farmers attrite from the sample between the baseline and the third follow up. In Rwamagana, the attrition was 12% (89/736). We instituted careful field protocols to assure the highest possible response rate. A major component of these protocols was sending in field mobilizers to visit the village before the enumerators to inform the village leaders about the upcoming survey and give respondents appointments. Collaboration with the local leaders in the villages was critical to mobilizing respondents for the survey. In case a respondent was not available at the first appointment, up to 2 more attempts were made to survey the respondent before marking them as unavailable. The main reasons for attrition are some households have permanently moved away from the site, households dissolved (no longer exists: or the main respondent missed more than 3 appointments during our survey period in the village.

There are two other major implementation challenges. First, mini kits were distributed behind schedule, which limited take-up. To mitigate this, we worked with the government to provide a second round of mini kits to the randomly-assigned farmers during Season C. Second, water user fees are not being implemented as planned by the government: in one of the three sites, the government approved a 50% reduction in fees. In all three sites, compliance with fee repayment is incomplete, and repayment is not being strongly enforced. This mitigates the power of our fee subsidies within the study, as it changes the expectations on penalties for those who do not pay their fees. This may reduce the effectiveness of the subsidy intervention. We are working with the government to understand how fee repayment infrastructure can be strengthened, as the recovery of operation & maintenance costs is paramount to ensuring the sustainability of irrigation investments. This policy concern will likely yield new policy ideas to be tested in the near term. Appendix A provides all the results and findings detailed below⁷.

4.2 Descriptive statistics and balance

The survey respondent is the household head. On average, the head is 49 years old. 27.8% of the household heads are female. Female household heads tend to be older; averaging 56 years old compared to 46 for men. Approximately 1/3 of household heads have no formal education, 1/3 have some primary education, and 1/3 have completed primary education or higher. At baseline, most reside in dwellings with adobe walls and dirt floors and rely on a pit latrine.

The sample population is rural households that rely on subsistence farming for their livelihoods. The median household owned 4 plots and cultivated 5 (rentals are common). Plots are very small: the median size is 5 ares (.05 hectares) and the average is 12 ares. The most commonly grown crops in the rainy seasons are dry beans, maize and sorghum. In the dry season, less than 1 in 5 plots are cultivated, and farmers typically only cultivate bananas.

⁷ Note that the table numbers listed in this section refer to the table numbers from Appendix A.

Crucially, in terms of balance, Table A2 indicates that our sample plots are balanced in terms of ownership and rentals, and that most sample plot owners on both sides of the canal owned the land for at least 5 years, or prior to the start of the irrigation construction. There is, however, some imbalance on plot size: log area (measured in hectares) is larger inside the command area than outside the command area.

4.2.1 Baseline impacts

In Table A15, we consider two additional impacts of command area construction. First, terracing occurred jointly with hillside irrigation. Although there was also meaningful terracing outside the command area to protect against erosion, there was more terracing inside the command area, as it is impossible to have hillside irrigation without terracing (as water would run off the sloped hillsides). We therefore note that our effects are the combined effect of terracing and access to irrigation; however, the absence of effects during the rainy season (and large effects during the dry season) suggest our results are driven primarily by access to irrigation (and not terracing). Second, rentals out to commercial farmers occurred inside the command area, as these commercial farmers were keen to take advantage of access to irrigation. These commercial farmers were private businesses exporting vegetables and they had negotiated land lease rates with the government. We do not have data on production by commercial farmers but note that these farmers were exclusively cultivating high-value horticultural crops; as such, the absence of these plots render our estimates conservative.

We also note that hillside irrigation systems were online in a small part of the sites in 2014 Dry and hillside irrigation was just beginning to come online in the 2015 Rainy seasons, the first surveys covered by the baseline. Thus, the baseline survey was completed shortly after the construction of the hillside irrigation schemes was completed. Tables A16 and A17 report impacts on agricultural outcomes in 2014 Dry and the 2015 Rainy seasons. Consistent with irrigation not having come fully online, we observe limited adoption of irrigation. In contrast to our main results from follow up surveys, at baseline cultivation is lower in the dry season inside the command area. This is driven by a combination of low adoption of irrigation and horticulture, and lower cultivation of bananas. These banana effects are partially explained by terracing, during which bananas were torn up to construct the terraces. These banana effects are smaller than in follow up surveys, and the share of plots cultivated with bananas is also lower outside the command area than in follow up surveys. Together, we interpret these results as farmers beginning to replant bananas following terracing, but less replanting occurring inside the command area than outside. As irrigation had come online by 2015 Rainy 1 and 2, rainy season results look similar to rainy season results in subsequent seasons – modestly lower cultivation, and significant but modest increases in adoption of irrigation and horticulture, and reduced banana cultivation. Third, we estimate impacts on inputs in Table A4, and output in Table A5. Consistent with the small increases in horticulture and modestly larger decreases in low input intensive bananas, we do not find consistent significant effects on input use, yields, sales, or measures of profits in the dry season or rainy season.

4.3 Impact analyses

4.3.1 Impacts of Irrigation

First, we note that all reported estimates are ITT unless otherwise specified. Any TOT estimates use adoption of irrigation as the endogenous treatment variable. The definitions of all constructed variables have been added as Appendix H.

Tables under section 4.1 in the appendix summarize the results of the overall impacts of irrigation. Command area plots are 15-19pp more likely to be irrigated during the dry season than plots outside the command area, and almost all this increase is explained by the transition to cultivation of high-value horticulture during this dry season. In contrast, adoption of irrigation during the rainy season is much lower, with increases of just 4-6pp. This transition to dry season horticulture substitutes for cultivation of perennial bananas, a less productive but less input intensive commercial crop; we estimate a decrease of 13-15pp in the command area, and therefore we observe no impacts on cultivation in the dry season⁸. Second, we find large increases in dry season input use, which are dominated by increases in household labor. These results are consistent with the transition from perennial bananas, which require little inputs and labor, into horticulture, which is highly input and labor intensive. To interpret these results, we conduct a treatment on the treated analysis under the assumption that the command area increases input use only through its effect on irrigation. Doing so, we find that adoption of irrigation increases household labor use, input expenditures, and hired labor expenditures by 350-430 person-days/ha, 25,000-35,000RwF/ha, and 15,000-25,000 RwF/ha, respectively. The impacts on household labor are particularly large – valued at a typical wage of 800 RwF/person-day, this labor would be priced at 280,000-345,000 RwF/ha, an order of magnitude larger than the effects on input expenditures or hired labor expenditures. Additionally, as reference, applying this labor to 0.3 ha (median household landholdings) of command area land would require roughly 4 person-months of labor during the 3-month dry season. In contrast, we find no effects on input use during the rainy seasons; this is consistent with access to irrigation, and not terracing, being the primary cause of these results.

Consistent with our estimates of impacts on input use, we find large increases in dry season agricultural production. Treatment on the treated analysis suggests adoption of irrigation increases yields by 300,000-400,000 RwF/ha, 50-70% of annual agricultural production. As horticulture is primarily commercial: each 1 RwF/ha increase in yields is associated with a 0.79-0.86 RwF/ha increase in sales. Once again, these results on outputs are consistent with differences between bananas and horticulture production. Additionally, these impacts on yields are much larger than our estimates of impacts on input and hired labor expenditures; our results suggest irrigation increases yields net of expenditures by 240,000-360,000 RwF/ha, a 46-70% increase in annual yields net of expenditures. However, we should not interpret this as impacts on profits, as it implicitly places no value on the large increases in household labor. If we instead value household labor at 800RwF/person-day, the median wage we observe, these impacts vanish

⁸ As bananas are perennials, plots cultivated with bananas typically have harvests in each season. In contrast, the rotations of staples and horticulture (or simply horticulture) that replace bananas may only involve two plantings and harvests, and we therefore see a modest decrease in cultivation during the rainy seasons of 5-10pp on a baseline of 81%.

completely. Therefore, the profitability of the transition to dry season horticulture enabled by irrigation depends crucially on the shadow wage at which household labor is valued.

Taken together, these results together suggest that irrigation leads to a large change in production practices for a minority of farmers. Those farmers cultivate horticulture in the dry season and a mix of horticulture, staples, and fallowing in the rainy seasons, they have substantially higher earnings in the dry season but similar earnings in the other seasons, and they invest more in inputs and much more in household labor in the dry seasons. Our estimates suggest that irrigation has the potential to be transformative in Africa, in light of the 46-70% increases in yields net of expenditures that we document from just three months of cultivation. At the same time, these results also suggest that the shadow wage, and therefore labor market frictions, are likely to be important for the decision to cultivate horticulture.

We include some additional tables to test the robustness of our results. First, Tables A25 – A28 present results using a difference-in-differences design. As there were already impacts of the command area construction in 2014 Dry and the 2015 Rainy seasons, discussed above, these results can be interpreted as the difference between the impacts of the command area construction in these seasons, and the impacts of the command area construction in later seasons. All emphasized results are robust to this specification. Second, Tables A29 – A32 present results controlling for the WUG having a member empowered as a monitor. The estimated impact of the command area in these specifications can be interpreted as restricting the analysis to use command area plots which did not have a member empowered as a monitor. As such, the estimated coefficients are very similar to the difference between our primary estimates of the impacts of the command area, and our estimates of the impacts of having a member empowered as a monitor; as the latter are typically not statistically significant, our estimates do not change much.

4.3.2 Minikits experiment

Minikits were first distributed in 17A. Section 3.2 present results of regressions which examines season-by-season effects of access to minikits. Table A33 indicates that there was a 44 percentage points increase in take up of the minikits in the 2017 rainy season and 36 percentage points increase in the 2017 dry season. The rate was less than 100% as farmers offered minikits were not obligated to receive them. We do not see significant impacts of the take up of minikits on outcomes of interest.

4.3.3 Subsidies experiment

Section 3.3 present results of regressions which examines season-by-season effects of the monitoring treatment. FF refers to receiving full subsidies in both seasons, FN refers to the treatment in which the farmer receives full subsidy in season 1 and no subsidy in season 2, and HF refers to the treatment arm in which farmers receive half and full subsidy.

Column 1 of table A40 depict that those receiving the FN subsidy are significantly more likely (at 5% level) to cultivate their land in the dry season. Similarly, as seen in column 1 of table A42, those receiving the FN subsidy are significantly more likely (at 5% level) to cultivate their land in the rainy season. Though cultivation increases for other treatments these are not significant. Similarly, farmers receiving the FN subsidy are significantly more likely (at 10% level) to irrigate their land in both, rainy and dry, seasons.

4.3.4 O&M experiment

Section 3.4 present results of regressions which examines season-by-season effects of the monitoring treatment. T1 refers to the treatment of empowering a monitor who could be selected from anywhere in the WUG and T2 is the treatment requiring a monitor to be selected from the top third of the secondary pipe.

For both, the rainy and dry seasons, we see that assignment of either WUG treatments does not lead to significant effects on almost all outcomes considered.

4.4 Heterogeneity of impacts

We test for heterogeneity of the impacts of each of our interventions with respect to gender of the household head; we find no consistent meaningful differences in the impacts of our interventions with respect to gender of the household head, and results are available upon request.

4.5 Follow up qualitative work

As mentioned in section 3.2, 3 Focus Group Discussions (FGDs) were conducted in one of the four sites (Karongi 13) to understand reasons for low irrigation take up. Through these discussions, we navigated through understanding farmers agriculture practices to set the tone of the conversation. This lead to asking understanding why most of the land in the irrigated area is not cultivated during the dry season, characteristics of the owners of the uncultivated land and what they think could be done for that land to be used. Following this, the conversation was taken towards understanding irrigation take up and challenges to the same. Through the discussions it became clear that one of the main reasons for low irrigation take up in the dry season land and labor market frictions. This is because the horticulture crops that are grown in the dry season require large amounts of labor and those farmers who have land in the irrigated areas do not necessarily have the amount of labor and are unable to hire the required to be able to make productive use of the land in the dry season.

5. Cost analysis

The construction of the irrigation canal cost USD 5.5 million in Nyanza; approximately \$12,700 per hectare of command area. In the two Karongi sites, the total cost is USD 2.4 million, approximately \$9,400 per hectare of command area. In Rwamagana, the construction of the 14.5 km long canal was contracted out for a value of USD 2.7 million. The irrigated area is 292 hectares; hence the approximate cost per irrigated hectare is \$9,250.

Building large scale irrigation canals are a huge economic cost which are not intended to be recovered in a span of 4 years. This is also indicated in the World Bank project document which says the costs are estimated to be recovered in 26 years (Figure 5). Therefore, the short-run benefits we document in the main RDD intervention are not usefully compared to the costs of overall scheme construction. Instead, we run cost-benefit analysis for the smaller interventions, which are more likely to have immediate impacts.

Figure 5: Excerpt from LWH project document indicating long run nature of project

3. For the purposes of the Economic and Financial Analysis (EFA), the LWH Project, which will run for four years and has two main technical components, is assumed to amount to a total of US\$45 million (including physical and price contingencies). The first component is the Capacity Development and Institutional Strengthening for Hillside Intensification, broken down into 4 sub-components: (i) Support to Farmer Organizations; (ii) Support to Improving Extension System; (iii) Support to Marketing and Rural Finance; and (iv) Support to MINAGRI and its Agencies. The second component is the Infrastructure for Hillside Intensification, composed of 3 sub-components: (i) Land Husbandry Infrastructure; (ii) Water Harvesting Infrastructure; and (iii) Irrigation Infrastructure. An additional component is included for effective project management within the new sector-wide approach (SWAp) at MINAGRI. From the point of view of the economic and financial analysis, these three components represent one integrated package and cannot be treated separately. Resettlement costs, environmental safeguards and soil erosion control measures are included in the project costs, which are integral part of the irrigation investment.

4. The technical life of these assets was estimated to be 25-50 years for irrigation infrastructure and 50-100 years for soil conservation measures, including radical terraces. This analysis adopted the most conservative figure and estimated the cost and benefit stream for a 50-year period; and assumed that water harvesting and irrigation infrastructure would be effective for 25 years, and thus a new set of investment for these infrastructure would be needed in Year 26.

5. After the 4-year project, the government would be expected to continue with the maintenance and recurring costs for the project to be sustained. This analysis assumed that the required annual costs to maintain the project would be equal to the last year's (Year 4) cost. A new set of resettlement costs and new set of investments for institutional and market development were also assumed to be needed by Year 26, which is conservative.

Source: Project Appraisal Document for the LWH project, World Bank Internal document

We conduct an economic evaluation of the O&M intervention and find a net benefit of \$125 per farmer. The complete cost-benefit analysis has been shared along with the report as Appendix D. The main costs involved were training the monitors and logistics in setting each of the trainings up. As the training was conducted in 2016, we inflate the costs to current year using an inflation factor of 0.1.⁹ For the benefits, we use the use in yields in the dry season as the benefits. We note that we can neither reject that the benefit of the intervention on yield was zero, nor can we reject that the intervention was cost effective.

6. Discussion

6.1 Introduction

6.1.1 Impacts of irrigation

Treatment on the treated estimates reveal that irrigation enables the transition to dry season cultivation of horticulture. While we find no effects on rainy season yields, labor, or inputs, dry season estimates correspond to 70% growth in annual cash profits. Despite the large effects we estimate, adoption is low: only 30% of plots are irrigated 4 years after canals became operational. At this level of adoption, the sustainability of hillside irrigation systems is in doubt: even the large gains in cash profits to adopters are unable to generate enough surplus to pay for routine maintenance costs.

6.1.2 Minikit experiment

We find no effects of receiving minikits on adoption of horticulture in our context, in contrast to existing work. The results suggest that access to agricultural inputs (seeds and fertilizer) was not the binding constraint. A closer analysis indicates that the farmers

⁹ We round up the inflation rate for 2016 and 2-17 as provided by the World Bank data to create the inflating factor.

who take up the minikits are the same farmers who would have been likely to cultivate horticulture absent the intervention. We see a 1-for-1 substitution of market inputs for the provided inputs. The results suggest that financial and informational constraints are unlikely to be a primary explanation for low and inefficient adoption of irrigation.

6.1.3 Subsidies experiment

We find no impact of fee subsidies. The reason for this is clear -- although we have a strong and large first stage on fees owed by farmers in administrative data, the impacts of subsidies on fees paid by farmers were 10% of the size of the impacts on fees owed, both in administrative data and self-reports. Moreover, the fees were implemented as land taxes and not charged based on irrigation use so as not to discourage adoption. In sum, at the low levels of enforcement observed during the 2017 Rainy seasons, they should not have affected farmers' production decisions, consistent with the results we find.

6.1.4 O&M experiment

We find no impact of empowering monitors. This is because O&M was highly effective in these irrigation schemes, and empowering monitors therefore had limited scope for changing O&M practices. Farmers reported 14% as many days without enough water during the dry seasons as they reported days using irrigation. Any event where conflict among water user group members caused insufficient water at some point during the dry season was reported for 3% of irrigated plots. This success was far from guaranteed in the early years of the schemes; site engineers have suggested that the combination of lower adoption of irrigation than the schemes are designed for and high compliance with water usage schedules among farmers have been the cause of this. Moreover, during the 2018 Dry season we found evidence that control water user groups adopted the intervention, as some members of control water user groups adopted the roles that were assigned to monitors.

6.2 Policy and program relevance: evidence uptake and use

The research team has a long-standing interaction with the Government of Rwanda, with PIs updating key stakeholders including Ministers, Permanent Secretaries, and Director Generals in the Ministry of Agriculture and RAB multiple times per year.

Results from the existing evaluation have already influenced the policy dialogue in the country and there is a strong appetite for evidence on best practices to improve the use of irrigation infrastructure. Because of this policy engagement, the government's senior leadership adopted a resolution "to exploit underutilized irrigated land leveraging efforts of young agricultural professionals while improving land use planning and resettlement" at the most recent (Mar 8-11, 2019) country leadership retreat. Results on effects of irrigation have also informed a core elements of the current strategic plan ([Strategic Plan for Structural Transformation in Agriculture Number 4, PSTA-4](#)¹⁰).

Given the low take up of irrigation despite high productivity of irrigation in Rwanda, the next step towards understand the constraints to adoption of irrigation and alleviating the same have been well received by the Ministry of Agriculture. In the academic paper

¹⁰ The irrigation study is cited on Page 48 of the PSTA-4

produced alongside this evaluation (Jones et al, 2019) we provide evidence that the adoption of irrigation is inefficient, and that land and labor market constraints contribute to the inefficient adoption. Future work in collaboration with the Rwanda Agricultural Board includes an upcoming randomized control trial on better understanding land market constraints as a tool to increase and sustain adoption in another irrigated site in Rwanda.

The results from this evaluation have also been an integral part of the discussion of setting up the new World Bank lending project “Sustainable Agricultural Intensification and Food Security Project (SAIP)” in Rwanda. Figure 6 below indicates the points where the learnings from this study were used in the project document.

Figure 6: Reference to study in SAIP project document



The World Bank

Sustainable Agricultural Intensification and Food Security Project (P164520)

77. **Irrigation sustainability is a challenge, as usage of the irrigation infrastructure is low and few farmers pay the required fees.** An impact evaluation of the irrigation investment under the LWH shows that positive impacts of the irrigations schemes are a result of adopting high-value crops such as horticulture. However, for large-scale irrigation, the positive impacts are concentrated among a subset of more commercial farmers, while subsistence farmers are less likely to benefit and less likely to pay water-usage fees though they do benefit indirectly through land and labor markets. The proposed project supports the GoR farmer-owned SSIT program to scale up its activities and increase outreach. This would allow farmers in areas bordering developed schemes to be able to irrigate smaller pieces of land and achieve good yield levels even during drought periods. This way, the project will enable them to cope with the negative impacts of climate change, while receiving the benefits from irrigation.
78. **Markets need to allow farmers to realize gains from trade to sustain the economic value of agricultural investments.** The impact evaluation of the LWH found that, despite higher harvest yields, sales values of produce do not see positive effects of the same scale, which indicates systemic inefficiencies related to production and yield. These findings also point to potential inefficiencies in input-output markets. The evaluation found that on the output front, market access and production surplus remain of central concern and suggested that localized marketing facilitation activities be the focus of future project interventions, while recognizing that institutional changes and large-scale investments will be required to address these market inefficiencies that may be beyond the scope of one project. It is envisaged that the integration of this project with larger projects such as the PforR could contribute to addressing the market inefficiency.

Source: [Project Appraisal Document for the SAIP project](#)

In addition, results from the minikit experiment influenced policymakers’ understanding of the constraints underlying low adoption. The experiment suggests that financial constraints are not binding for commercial agriculture with traditional horticulture crops in the hillside schemes, and this has influenced the government’s approach to increasing adoption of irrigation.

6.3 Challenges and lessons

For the three interventions within the command area – O&M, minikits, and subsidies – risks to internal validity are extremely limited as the interventions are randomized. For the impact of irrigation, there is a possibility that farmers have endogenously sorted on either side of the boundary. We conduct analysis on the sample of farmers who were working on either side of the boundary just before changes in the regime and track those farmers over time, which mitigates this concern.

There are potentially more serious issues of external validity. Our sample is based on only four irrigation sites in Rwanda. Since variation is at the individual or block level, we can still achieve statistical power in our estimation framework. However, there are not enough sites to guarantee that results would be similar at other sites which may be built. This problem seems likely generic to infrastructure interventions. On the other hand, close work with the SPIU and MINAGRI interest in results suggest that implications from our evaluation will have strong impact on policy.

7. Conclusions and recommendations

We present results on the impacts and sustainability of four hillside irrigation sites in Rwanda. Comparing plots just above the main canal (command area) to those just below the canal (command area catchment) allows us to retrieve causal estimates of irrigation on a range of outcomes, including plot-level productivity.

Using data from very proximate plots which receive differential access to irrigation, we document that the construction of an irrigation system leads to a 70% increase in cash profits. These profits are generated by a switch in cropping patterns from perennial bananas towards a rotation of dry-season horticulture and rainy-season staples, which itself is associated with an increase in input intensity. In our context, the primary increase in input demands is for household labor, which is utilized intensively on horticulture and minimally on banana cultivation. The results show that irrigation has a positive and significant impact on value of production and sales.

Additional RCTs run on the margin of this large investment suggest that minikits, irrigation fee subsidy and free demonstration resources do not have a significant impact. Our recommendation is to carefully think through the design of such programs so that each program works well in complement to the other.

Irrigation has huge potential benefits for smallholder farmers; the increases in yield and profits realized in the schemes are large and economically meaningful for smallholder farmers. However, we observe only a minority of farmers adopting this technology four years after introduction. Given the returns identified above, we take this as evidence that the existence of a productive technology is not itself sufficient to generate majority adoption in all agricultural contexts.

As a grants reporting document rather than an academic paper, this report is meant to present only on the raw impact evaluation of the irrigation scheme and the associated randomized controlled trials. In the academic paper produced as part of this effort (Jones et al, 2019) we explore further which factors may constraint irrigation take-up. In that paper, we use a series of tests to document that the low take-up of irrigation is inefficient, and we provide further evidence that land and labor market constraints reduce irrigation-take-up. We therefore conclude that addressing land and labor market constraints is key to increasing and sustaining adoption.

Online appendixes

Online appendix A

<https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1085-Rwanda-Irrigation-Online-appendix-A.pdf>

Online appendix B

Online appendix B1

<https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1085-Rwanda-Irrigation-Online-appendix-B1-BL-enumerator-manual.pdf>

Online appendix B2

<https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1085-Rwanda-Irrigation-Online-appendix-B2-BL-RW-enumerator-manual.pdf>

Online appendix B3

<https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1085-Rwanda-Irrigation-Online-appendix-B3-BL-RW-survey-instrument.xlsx>

Online appendix B4

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Online appendix B5

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Online appendix B6

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Online appendix B7

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Online appendix B8

<https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1085-Rwanda-Irrigation-Online-appendix-B8-FUP1-survey-instrument.xlsx>

Online appendix B9

<https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1085-Rwanda-Irrigation-Online-appendix-B9-FUP2-enumerator-manual.pdf>

Online appendix B10

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Online appendix B11

<https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1085-Rwanda-Irrigation-Online-appendix-B11-FUP3-enumerator-manual.pdf>

Online appendix B12

<https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1085-Rwanda-Irrigation-Online-appendix-B12-FUP3-survey-instrument.xlsx>

Online appendix C

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Online appendix D

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Online appendix E

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Online appendix F

<https://www.3ieimpact.org/sites/default/files/2020-03/DPW1.1085-Rwanda-Irrigation-Online-appendix-F.xlsx>

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