Bringing the Water-Efficiency Benefits of Precision Irrigation to Resource-Constrained Farms Through an Automatic Scheduling-Manual Operation Irrigation Tool

by

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Abstract

As global populations increase and freshwater supplies decrease, improving farmers' adoption of water-efficient irrigation equipment and practices is crucial. This aim is particularly imperative in resource-constrained regions like East Africa (EA) and the Middle East and North Africa (MENA) where existing precision irrigation solutions—which are designed to achieve high water efficiencies—often do not meet the needs of farmers. In these regions, farmers prefer their current manual practices, or they may not be able to easily purchase, install, or maintain traditional precision irrigation equipment. This work aims to bring the water-efficiency benefits of precision irrigation to resource-constrained farmers by understanding and meeting their specific needs.

First, this work sought to elucidate the differences between the diverse types of EA farmers and to understand if opportunities exist for new irrigation products targeted to these farmers. An interview-based market assessment was conducted to reveal distinct market segments and each segment's values regarding irrigation systems. Then, a techno-economic feasibility analysis was conducted to reveal which irrigation methods and energy sources would be most promising for each segment. Four market segments were found: the traditional smallholder, the semi-commercial smallholder, the medium-scale contract farmer, and the remote farmer. The remainder of this thesis focuses on the medium-scale contract farmer who would value low-cost prediction capabilities and solar-powered drip irrigation systems optimized for profit. The identified opportunities for innovation in this work can guide irrigation designers as they develop new systems that directly serve farmers' needs.

The second aim of this work targeted medium-scale contract farmers in EA and a similar segment of MENA farmers. Functional requirements were proposed for a tool that could address the efficiency needs of these farmers while integrating into their current manual practices. To meet these requirements, a design concept for an automatic scheduling and manual operation (AS-MO) user experience (UX) was proposed. Storyboards and a prototype demonstration of the AS-MO UX were evaluated by farmers and key market stakeholders in Kenya, Jordan, and Morocco. Farmers in Kenya and Jordan in particular valued the proposed UX because they want increased efficiency on their farms without installing automatic valves for cost and complexity concerns. Interviewees provided feedback on how to improve the tool's design in future iterations.

Finally, this work describes functional AS-MO tool prototypes that were installed on a farm in Jordan and a farm in Kenya. To understand how this tool performs under real farm conditions, these prototypes were designed to deliver a long-term AS-MO UX to study participants. The prototype monitored local weather conditions, generated water-efficient schedules using an existing scheduling theory, and notified users' phones when they should manually open or close valves. The irrigation practices of participants using the AS-MO prototype were compared to conventional practices. After 11 weeks of use, study participants also demonstrated successful use of the prototype on a daily basis. Irrigation events were measured on the field to show that users confirmed 93% of the scheduled events correctly using the tool's interface. Further, of the irrigation events that did occur, a majority of their durations fell within 15% of the scheduled duration. Results from this work and feedback from study participants can continue to improve the design of the proposed AS-MO tool and its UX. If adopted at scale, this tool could increase the adoption of water-efficient irrigation practices on resource-constrained farms that are not served by existing precision irrigation technology, improving food security and sustainable agriculture in EA and MENA.

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Chapter 1

Introduction

The overall aim of this thesis is to design a technology that enables resource-constrained farmers to adopt sustainable irrigation practices.

The United Nations' second Sustainable Development Goal (SDG 2) aims to achieve food security and improved nutrition by 2030 [112]. Introducing irrigation on farms is known to be an effective path toward food security, especially in arid and semi-arid regions where farmers have limited access to rainwater [10, 95, 83]. Irrigation has also been shown to help farmers grow more nutritious crops, like vegetables and fruits [16]. Unfortunately, increasing irrigation can have negative effects on water resources and can use a significant amount of energy. This directly conflicts with the final aim of SDG 2: to promote sustainable agriculture. Currently, irrigation accounts for 70% of global freshwater use, and crop production accounts for 4% of global energy consumption each year [34, 57]. Despite many past and ongoing efforts in this space, increasing irrigation sustainably remains a challenge.

Addressing this challenge is especially difficult for resource-constrained farmers. This work focuses on resource-constrained farmers because they represent a large number of farmers worldwide. 49% of the farms in the world, or nearly 280 million farms, are in low-income or lower-middle-income countries, meaning there is an abundance of economically-constrained farms [70]. This thesis specifically focuses on farmers in two geographic regions: East Africa (EA) and the Middle East and North Africa (MENA).

In EA, 40% of the population, or 180 million people, were estimated to be food insecure in 2020 [11]. In EA, only 2% of the cultivated land is irrigated [55, 30]. When this figure is compared to the worldwide average of 20%, it shows a significant lag in the adoption of irrigation equipment. Studies have shown that increasing irrigation in EA could contribute greatly to achieving food security in this region [78, 6, 86, 87].

MENA shows similar levels of food insecurity as EA with 33% of the population, or 180 million people, facing this challenge in 2019 [35]. Unlike EA, MENA farmers have adopted irrigation at higher-than-average rates, with 37% of the cultivated land under irrigation [55, 30]. Irrigation is often necessary in MENA because this region is one of the most arid in the world; 61% of the population is exposed to high water stress [124, 118].

Farmers in both EA and MENA are in need of affordable, sustainable irrigation technologies. The following chapters provide more background on the current state of irrigation in these two regions as this work proposes and analyses an approach for how to achieve this.

The overall aim of this thesis is accomplished through three specific aims:

- Chapter 2 covers a needs assessment of the EA irrigation market. Four distinct market segments of small- to medium-scale farmers are elucidated, as well as the farmers' corresponding user needs and design requirements for irrigation systems that meet those needs. Candidate system architectures for each market segment were mapped out to provide proposed technology solutions. These results can aid irrigation system designers so they can create more targeted products, increasing the likelihood of irrigation adoption among EA farmers.

- Chapter 3 proposes the concept of a semi-manual/semi-automatic irrigation tool and describes how this concept was evaluated by potential users and key market stakeholders in Kenya, Jordan, and Morocco. The user needs of a specific market segment—the medium-scale contract farmer—were translated into this design concept. The tool concept and its associated user experience were assessed by interview participants in three countries to evaluate how it could best enable farmers to confidently and economically adopt water- and energy-saving technology on their farms.

- Finally, Chapter 4 details a functioning prototype of this semi-manual/semi-automatic tool and presents the results from a long-term tool demonstration on a Jordanian farm and a Kenyan farm. During this demonstration, it was found that this prototype successfully integrated earlier findings about farmer practices to deliver an easy-to-use experience for farmers. When combined with recent results validating the tool's underlying scheduling theory, farmers used the tool in a way that indicates its water-saving potential. Demonstrating this technology in real farm conditions was an important step toward realizing a tool that could be successfully adopted by resource-constrained farmers in EA and MENA.

Chapter 2

Identifying opportunities for irrigation systems to meet the specific needs of farmers in East Africa

2.1 Introduction

The objective of this study was to identify new opportunities to enhance the adoption of irrigation systems in East Africa (EA) by elucidating and targeting the needs of distinct market segments. This study sought to understand if new opportunities exist for sustainable irrigation products targeted at small-to-medium scale farms. In 2020, an estimated 39.4% of EA's population was food insecure, a number that will still remain above 20% in 2030 [11]. An effective path toward increasing food cultivation is increasing irrigation [10, 95], a farming practice that is not widely adopted in EA. Only 2.2% of the cultivated land in EA is currently irrigated, compared to 22.7% in North Africa, 39.1% in Asia, and 19.7% worldwide [55, 31]. In order to meet food demands, governments, non-governmental organizations (NGOs), and private companies have been looking for solutions to increase irrigation, from treadle pumps to drip irrigation kits to motorized pumps [78]. Despite the support, no one solution or set of solutions has been able to significantly increase EA irrigation adoption.

Existing irrigation products do not currently meet the cost and performance requirements for much of the market. A challenge in solving this problem is the diversity of farmers in EA. Small- and medium-scale farmers in EA (who we consider to be farmers cultivating 5 ha or less) account for 95% of Sub-Saharan African farm holdings [70]. These farmers likely have a wide range of irrigation needs, including typical crops grown, irrigation schedules, and farm area. Further, they likely have diverse reasons for irrigating (e.g., subsistence reasons or business-growth reasons). If that is the case, different segments of farmers would respond better to irrigation systems that deliver value propositions targeted to their specific situations. In literature, there has been a large focus on smallholders who cultivate less than 2 ha [95, 78, 94, 93, 3, 15, 17, 61]. There are limitations for these farmers, many of whom have very low abilities to pay; the prices they are able to afford cannot buy them the desired performance they need from an irrigation system. At the same time, there are a large number of farms in the 2-5 ha range that are not being targeted because their cost and performance requirements are not well understood in the current literature. To address these challenges, this work investigated the design of irrigation systems targeted at multiple, distinct market segments of farmers.

In addition to the need for higher food security in EA, there is a need to accomplish this goal sustainably. Expanded irrigation, like that which came with the Green Revolutions in China and India, increased food security but depleted the countries' water resources [120, 58]. Africa might be going through a similar revolution [92, 13], so it is important to understand how water-saving technologies or emission-free energy sources can be introduced while still meeting the needs of farmers. In this study, both individual farmers' and society's needs were considered.

This study addressed the following research questions:

- What market segments exist in the full range of small- to medium-scale EA farmers? What are the user-driven needs of farmers in these segments?
- How do those needs translate to value propositions of irrigation systems that articulate pathways to achieve the most desired irrigation benefits within the

constraints of each segment?

- What technical requirements come from the user needs and value propositions? How do those requirements compare to the performance of feasible systems?

These questions were answered in a two-part analysis. An interview-based market assessment informed the current state of the irrigation system market in EA by segmenting the range of small- to medium-scale farmers into distinct user groups and eliciting these farmers' needs and corresponding value propositions. A technical and economic analysis informed which technologies could be feasibly realized from an energetic standpoint, and the results propose sets of requirements for irrigation products that could deliver tailored value to farmers. This work highlights opportunities for technical innovation that could increase the likelihood of user-driven irrigation adoption in EA.

2.2 Interview-based market assessment

2.2.1 Interviews with farmers and key market stakeholders

Qualitative interviews with farmers and key market stakeholders were used to elicit information about the current irrigation market and farmers' typical irrigation preferences, challenges, constraints, and agricultural goals. Throughout 2019–2021, 33 semi-structured interviews with farmers were conducted. Interviews guided subjects through questions about their likes and dislikes of their current irrigation systems, noticeable improvements of their current system over any previous irrigation methods, their typical irrigation schedules, their household and agricultural water usage, their well installation process (if applicable), their ability to repay their current systems, their willingness and ability to pay for new equipment, and their future plans for improving their farms. A list of example interview questions can be found in Appendix A.

Interview subjects were selected to cover a range of field sizes and levels of irrigation experience, ranging from irrigating small vegetable gardens using buckets to managing flower export businesses using drip irrigation in greenhouses. Subjects were recruited from Kenya, Ethiopia, and Zambia, and interviews had a typical duration of 30 to 60 minutes. Twenty-four interviews were conducted on these farmers' farms, several of which were conducted through the use of a local translator. Visiting farms allowed us to include photos and notes of farm conditions as further qualitative data. These 24 farmers were recruited through private irrigation companies or NGOs: SunCulture, Futurepump, iDE, Water4, Inc, and Illumina Africa. Nine interviews were conducted over the phone. These farmers were recruited through an online survey that was promoted by irrigation equipment suppliers. All interview protocols were approved by the Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects.

To understand the irrigation products currently offered in the EA irrigation market and the envisioned future of the market, 47 semi-structured interviews with key, non-farmer stakeholders were conducted throughout 2019–2021. Stakeholders who were knowledgeable in the preferences and constraints of small-to-medium scale farmers from a range of diverse perspectives were recruited. Stakeholders represented government agencies, NGOs, irrigation equipment distributors, agricultural input suppliers, borehole drilling companies, agricultural research organizations, agricultural universities, and microfinance institutions (MFIs). Each type of stakeholder was asked about how their area has changed in recent years to improve irrigation in EA, what irrigation would look like in their ideal perspective, and what it might take to reach that point. Sample questions can be found in Supplemental Information 2. Four interviewees were interviewed more than once to provide follow-up information. Data from these 30- to 60-minute-long interviews supplemented the farmer interviews because they provided insight into the current state of the irrigation market from broad policy and technology perspectives.

2.2.2 Market segmentation based on user-driven irrigation needs

As expected, the irrigation needs and contexts of the interviewed farmers were diverse (Table 2.1). Farmers had access to a variety of different water sources, irrigated a wide range of farm areas, and grew different crops. Interviewed farmers spent varying amounts of time in the fields, and they did not all have the same irrigation schedules as each other. They had various financial constraints when thinking about the lifetime cost of a system and how long they expected that life to be. These variations in responses were examined to identify clusters of similar farmer traits, which were identified as unique market segments. Farmers were grouped together based on the following factors:

- Their farms were similarly sized, and they were located in similar regions (e.g., rural or peri-urban)
- They cultivated the same types of crops (e.g., fruits, vegetables, or grains), and they used those crops for the same reasons (e.g., for in-home consumption or for market selling)
- They had similar economic profiles in terms of willingness and ability to invest in irrigation equipment
- Their current irrigation practices were similar in terms of experience on similar equipment, irrigation knowledge or training, irrigation scheduling, and maintenance
- Their desire for additional value-adds that an irrigation system could offer (e.g., cell phone charging or solutions for remote farm management).

Segmentation yielded four distinct market segments:

- The traditional smallholder (10 farmers in this segment were interviewed)
- The semi-commercial smallholder (14 farmers were interviewed)
- The medium-scale contract farmer (7 farmers were interviewed)
- The remote farm owner (2 owners were interviewed)

Table 2.1: Summary of user-driven irrigation needs and value propositions for the four market segments discovered.

	Traditional smallholder	**Semi-commercial smallholder**	**Medium-scale contract farmer**	**Remote farm owner**
Water source(s)	Surface water or shallow wells up to 10 m deep	Surface or shallow wells/ boreholes up to 25m deep	Boreholes up to 100m deep	Boreholes up to 100m deep
Farm area irrigated	0.125 ha	0.25 ha	2–5 ha (this analysis uses 4 ha)	1–4 ha (this analysis uses 2 ha)
Irrigation scheduling practices	Willing to irrigate 4 hrs/day Can be flexible with crop subsections as needed	Willing to irrigate 6 hrs/day Can be flexible with crop subsections as needed	Willing to irrigate 7 hrs/day Crop subsections are ≥ 0.2 ha and take ≥ 0.5 hrs to irrigate	Willing to irrigate 7 hrs/day Crop subsections are ≥ 0.2 ha and take ≥ 0.5 hrs to irrigate
Crop types and intended use for crop	A mix of low-value crops (e.g., maize) and high-value vegetables (e.g., cabbage and tomato) Intend to consume $>90\%$ of crop yield	High-value vegetables (e.g., cabbage, tomato) and fruits Intend to consume $>70\%$ of crop yield and sell $>30\%$	High-value crops (e.g., tomatoes, cabbage, herbs, fruits) Intend to sell $>95\%$ of crop yield	High-value crops (e.g., tomatoes, cabbage, herbs, fruits) Intend to sell $>100\%$ of crop yield
Investment timescale	2–3 seasons (this analysis uses 1 year)	2–3 years (this analysis uses 3 years)	5-10 years (this analysis uses 5 years)	5-10 years (this analysis uses 5 years)
Lifetime cost over investment timescale	300 USD; 200 USD before value add-ons	1300 USD; 1000 USD before value add-ons	18,000 USD; 15,000 USD before value add-ons	9000 USD; 7500 USD before value add-ons
Non-irrigation value add-ons	Phone charging and home lighting; Under 50 kg for portability	Phone charging, home lighting, power for small home appliances (e.g., TV, fan, minifridge, and cooking appliances)	Increased data and prediction (irrigation, pests, disease, markets); Flexibility of system based on farm characteristics	Solutions for improved remote farm management; Same value-adds as medium-scale contract farmer
Core value proposition of an irrigation system	A low-cost, portable irrigation system that replaces human power and enables cell phone charging and home lighting	An irrigation system that helps farmers grow their businesses and lifestyles	An irrigation system that maximizes farmers' profits	An irrigation system that farmers can monitor from the city and provides them with additional income

These results allowed us to generate hypotheses about the irrigation needs of farmers in the different segments. These hypotheses were then validated with data from stakeholder interviews based on their knowledge of many farmers' behavior and from a literature review. These hypotheses resulted in qualitative farmer profiles that describe the user-driven irrigation needs of each market segment. The following sections present these short profiles, elaborating on the needs summarized in Table 2.1. Further elaboration on, and citations for, details of these profiles are provided in Appendix B.

Profile of the traditional smallholder

As subsistence farmers cultivating on small, rural plots (on average 0.125 ha), the main farming motivation for traditional smallholders is to grow food for their families. The vast majority of traditional smallholders have minimal or no irrigation experience. Of those who do irrigate, most rely on manual irrigation. Attitudes towards manually-powered pumps with low capital costs, such as a treadle pump, revealed both the high value placed on low-cost irrigation and the high physical toll of supplying the water manually. Attitudes toward risk and income generation patterns suggest that traditional smallholders tend to be very risk-averse and would value a system that they know they could pay for in 2–3 seasons' worth of profits. Traditional smallholders' risk adverseness also leads them to diversify their crop selections (including both grains and vegetables) and their income sources, using this as a way to mitigate risk. This means that traditional smallholders are not willing to invest all their time and money in farming activities. Farmers also value more than just the ability to irrigate. For example, increasingly more farmers in this segment have home lighting and cell phones.

Profile of the semi-commercial smallholder

The semi-commercial smallholder was likely a traditional smallholder at one time. Now they have moved away from subsistence farming, seeing how they can start a small farming business. Compared to the traditional smallholder, they are more willing to invest both time and money in equipment that has a promising return on investment because they have seen past success in agriculture. Compared to traditional smallholders who have diverse income sources, farmers in this market segment are more focused on farming as their main income source. Therefore, they are able to dedicate more irrigation time per day than traditional smallholders can. Semi-commercial smallholders grow largely the same types of crops as traditional smallholders, with a slightly higher focus on fruits and vegetables over grains. While still located in rural areas, semi-commercial smallholders are quick to implement new agriculture techniques when they have developed access to the right resources. Like traditional smallholders, farmers in this segment are also interested in system capabilities beyond just irrigation. Interview results suggested they could derive value from small home appliances, like televisions and pressure cookers, and they are willing to pay for these items.

Profile of the medium-scale contract farmer

Medium-scale contract farmers run full-time farming businesses to feed the growing cities in EA. They cultivate medium-sized farms (typically 2-5 ha) in peri-urban areas. Farmers in this market segment invest in their businesses. Intending to sell >95% of their produce, they cultivate high-value crops like tomatoes, herbs, and fruit. Medium-scale contract farmers have advanced irrigation experience compared to smallholders. They employ seasonal and full-time laborers who irrigate, weed, plant, and harvest. Because farmers have this additional help, they are willing to spend the whole solar day irrigating. These farmers focus on selling their produce, so the appearance and size uniformity of their crop is important.

Profile of the remote farm owner

The remote farm owner lives in a city but owns or rents land in a nearby peri-urban region. They farm as a hobby or as a way to make supplemental income while investing in the land. While the remote farm owner may be involved in making big decisions about the farm, they are not present on a daily basis. Instead, they hire farm managers and laborers to run the farm for them. The remote farming market segment is an emerging one and not all problems with managing a farm remotely have been solved, so there is risk involved for the owners. Interviewed farm owners cited instances where hired laborers claimed to have completed work that was not done on the farms. Farmers in this segment have the capital to invest in irrigation systems, but they do not intend for farming to be their main income source.

2.2.3 Value propositions of irrigation systems for each market segment

The farmer profiles were used to gain insights into the design constraints and performance aspects that are considered most significant or highly valued by farmers in each market segment. These insights were used to build value propositions for irrigation systems that could fulfill the needs of farmers in each market segment (Table 2.1). These value propositions are discussed further in the following sections.

Traditional smallholder

The value proposition of an irrigation system designed for traditional smallholders is **a low-cost, portable irrigation system that replaces human power and enables cell phone charging and home lighting**.

First, the system must replace human power to provide value. Many EA farmers that have come out of poverty have done so using human-powered irrigation [64]. This is hard work. A system that replaces the human as the energy source could allow farmers to drastically improve their quality of life. Further, with the introduction of a system that replaces human power, farmers could shift their efforts to other income-generating tasks. Assuming they would want to spend about half their time on other income-generating activities, a system that only requires a farmer's attention for 4 hrs/day would satisfy this need.

Second, a system must be portable. Stakeholders noted that theft of irrigation equipment is an issue for smallholders, so farmers should be able to bring the equipment inside their homes each night. Smallholders do not necessarily cultivate on plots of land nearby their homes, so they need equipment that is easily transported, a maximum of 50 kg [38].

Third, a system that enables cell phone charging and home lighting would provide additional value that a standalone pump could not. The growing number of traditional smallholders with cellphones and access to home lighting shows that these farmers may value more than just the irrigation ability of a system [77, 24]. Bundling in-home lighting and phone-charging capabilities with an irrigation system may provide additional value to farmers that promotes adoption. Benchmarking against current products that offer these capabilities, we conclude a system should provide power for three home lights in the evenings and the daily charge of two cell phones in addition to fulfilling irrigation needs.

Fourth, the system must be low-cost, with a 300 USD target cost paid over three seasons. Traditional smallholders' high-risk aversion suggests they are unlikely to invest in an agriculture product that is not guaranteed to benefit them in a short time scale (on the order of 2–3 seasons). KickStart International concludes that 200 USD is a target capital cost for a system that fills a similar set of irrigation needs to what is described in this work [38]. However, KickStart's proposed system does not provide the additional cell phone charging and home lighting value that this work identifies. Adding these features (valued at 100 USD by interviewed farmers) to KickStart's estimated 200 USD, we estimated a lifetime target cost of 300 USD would best serve this market.

Finally, the system must fulfill the irrigation needs of the traditional smallholder. These subsistence farmers grow a variety of crops to feed their families, ranging from low-value crops like maize to higher-value vegetables like cabbage. Given this range of crops, cabbage was selected as a representative crop because it captures the higher end of what a traditional smallholder might expect in terms of water demand. Because they are primarily growing for their families and because their land holdings are small, they only need to irrigate about 0.125 ha. The water sources available to these farmers are surface water and shallow wells or boreholes up to 10 m deep.

Deeper sources are neglected because they would be too expensive for a traditional smallholder to install without the support of the government or an NGO.

Semi-commercial smallholder

The value proposition of an irrigation system designed for semi-commercial smallholders is **a system that helps them grow their businesses and lifestyles**.

First, the system must meet the farmer's changing business needs. Because semi-commercial smallholders are growing businesses, they are good candidates for a system that adds on or switches out components to improve its irrigation performance over time. These farmers' ability and willingness to learn new farming techniques further reinforce the value this feature could deliver.

Second, the system must accommodate the farmer's changing lifestyle. A system should at least start with the capability to light a home and charge a cell phone as seen with the traditional smallholder. The system should further be able to power small home appliances as the farmer's family purchases them, including a television, cooking appliances, a chaff cutter, an egg incubator, fans, or a minifridge (all examples given in interviews).

Third, the system must meet a semi-commercial smallholder's irrigation needs. Based on averages from interviews, it was found that farmers are willing to irrigate their 0.25 ha of land for up to 6 hrs/day. Shallow groundwater up to 20 m deep has been shown to be an accessible, strategic resource for many smallholders throughout EA [46]. However, existing products that serve a small percentage of this market operate at slightly deeper depths. In particular, SunCulture's RainMaker2 with ClimateSmart™ Battery is a photovoltaic (PV)-powered irrigation system that is designed to operate best at 32 m pressure head [104]. Targeting between these two values, this analysis uses 25 m as the representative water source depth for this market segment. This segment sells more high-value crops, so tomatoes are used as a representative vegetable.

Finally, the system must meet the semi-commercial smallholder's tight budget constraints. Thirteen out of 14 interviewed farmers owned Futurepump or SunCulture PV-powered irrigation systems. Depending on the configurations, these systems cost 600–1550 USD and are paid for over 2–3 years. Using these systems as benchmarks of viable systems in this market segment, a target cost of a novel system was set at 1300 USD, paid over three years. The system proposed in this work has higher flow rates than these systems, but we keep 1000 USD (the average cost of SunCulture and Futurepump systems) for the irrigation system alone, knowing that it has been successful for many existing farmers. 300 USD worth of add-on features (e.g., appliances) brings the total target cost to 1300 USD. While successful products exist for some semi-commercial smallholders, there are still millions of farmers in this segment who have not adopted one of these products, demonstrating additional value needed from improved irrigation performance as farmers grow their businesses and lifestyles.

Medium-scale contract farmer

The value proposition of an irrigation system designed for medium-scale contract farmers is **a system that maximizes their profits**.

The system can maximize a farmer's profits in two ways: by minimizing expenses and by maximizing revenue. A system can minimize expenses by decreasing operating costs, decreasing capital costs, and decreasing labor needs. Selecting an appropriate irrigation strategy helps farmers decrease their operating and capital costs, which this works aims to address.

Labor costs can be decreased by introducing automation on a farm. According to irrigation an interviewed system designer, large-scale farmers (who are not examined in this work) may use a high degree of automation on their fields. This technology is out of reach for many medium-scale farmers due to its high expense. One farmer remarked that he is ready to automate his irrigation, but a company quoted him 38,000 USD for a fully automated system for his nearly 1 ha farm. Another farmer who recently installed a 30,000 USD system did not yet have automation but said he would consider purchasing it if it were about 10% of the system cost. There is a demonstrated need for more affordable automation in the medium-scale contract farming market.

A system can maximize a farmer's revenue by providing increased data and prediction tools, aiding in more effective farming. Current apps help farmers to understand market trends so they can make educated decisions about harvesting [129, 37]. In the Australian market, research is being done to help farmers predict their yields and increase farm profits [109]. A system that can help farmers plan for unexpected weather, market, disease, or pest trends could provide great value in influencing how farms are managed.

As always, the system must meet the farmer's irrigation needs. For the scope of this work, we use a representative farm that is 4 ha of high-value crops and is irrigated using water from 100 m deep boreholes. The managing director of Hydro Water Well(K)Ltd. has been drilling in EA for the past 23 years, and he shared the company's logs of their 2470 boreholes. The most common borehole depths were between 100–125 m. This stakeholder serves more than just medium-scale contract farmers but agreed that many of his customers who fit this profile had boreholes about 100 m deep.

The system must be flexible based on differing farm characteristics. This work uses a representative 4 ha farm with a 100 m deep water source for the analysis, but in reality, medium-scale contract farms are diverse. Some might use a surface water source to irrigate 5 ha while others might use a 200 m deep well to irrigate 2 ha. To be successful, irrigation equipment for this market must capture most cases. Some equipment, like drip irrigation lines or PV panels, scales directly with varying farm characteristics. For other components, like pumps, a series of different options might be necessary. Due to this anticipated flexibility, one central system controller that operates well with these changing components could provide great value.

Finally, the system must be worth the farmer's monetary investment. Based on data gathered about the cost of existing medium-scale contract farmers' systems (see Appendix B), we set an estimated lifetime cost for the system at 18,000 USD, paid over five years. Because farms in this segment have a large range of sizes and water source depth, this amount can vary, but 18,000 USD is used for the representative farm parameters shown in Table 2.1. Excluding any sensors or a controller that would provide additional value, this cost lowers to an estimated target of 15,000 USD for just the irrigation components of the system. However, more important than meeting this cost target is clearly demonstrating that such an investment would increase a farmer's profit.

Remote farm owner

The value proposition of an irrigation system designed for remote farm owners is **a system that farmers can monitor from the city and that provides them with additional income**.

First, because the farm is an investment for the owner, the irrigation system must be profitable. Farms in this segment look similar to medium-scale contract farms because selling crops for profit is a main motivation. Remote farm owners hire managers with similar levels of agricultural experience as medium-scale contract farmers. However, the size of the irrigated area depends on the capital a remote farm owner is willing to invest. They have not yet seen past success in agriculture the way a medium-scale contract farmer might have, so for this analysis, a smaller, 2 ha irrigated area is estimated. The target costs are also scaled by a factor of 0.5, setting the target of the entire system at 9000 USD and the irrigation components alone at 7500 USD.

Second, the system must allow for remote monitoring. Available products and services do not yet support the remote farm owner in this respect. A system that could track weather, soil moisture, fertilizer application, and irrigation activity would provide great value and a sense of confidence to remote farm owners. However, an irrigation system alone might not fulfill all the remote farm owner's needs. Interviewed remote farm owners noted how difficult it was to manage and trust the laborers they have hired to manage the farm. Based on these types of challenges, we found a need for a professional farm management service that remote farm owners could adopt on their farms.

2.3 Technical and Economic Feasibility Analysis

2.3.1 Estimating the cost of an irrigation system

The farmer profiles and value propositions that resulted in subsection 2.2 gave us quantitative performance requirements that must be met to satisfy user needs in each market segment (Table 2.1). To estimate the cost of delivering this performance, a technical and economic model was built. This model was used to assess a variety of irrigation strategies, including common and emerging strategies. An "irrigation strategy" is a combination of an energy or power source plus an irrigation method (e.g., grid electricity + sprinkler irrigation). This model incorporates the user-driven irrigation needs, parameters relating to the cost and performance of irrigation strategies, and pump cost estimations.

For each irrigation strategy, system operating points (flow rate Q [m3/hr] and total dynamic head h_{tot} [m]) were calculated using

$$Q = 10\ (W_c\ A_{field}\ f_w)/t_{irr} \tag{2.1}$$

and

$$h_{tot} = h_{water} + h_{equip}, \tag{2.2}$$

where W_c is the daily crop water requirement [mm], A_{field} is the field's irrigated area [ha], ${f_w}^1$ is a unitless water factor specific to the irrigation equipment's water usage efficiency, t_{irr} is the daily irrigation time [hr], h_{water} is the head of the borehole or well [m], and h_{equip} is the head of the irrigation equipment [m].

Submersible multistage centrifugal pumps are suitable to use in boreholes and wells commonly found in EA. For each of the cases, a suitable pump with the best efficiency point closest to the farm's operating point (Q and h_{tot}) was chosen. Pumps

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[1] The water factor describes how much water a specific irrigation method uses. It is a unitless ratio of the volume of water used by the irrigation equipment over the volume of water needed by rainfall to yield the same amount of crop. Irrigation methods with low water factors save water without sacrificing crop yield.

were selected from Alibaba.com's online catalog, a source for the low-cost pumps commonly found in EA. The pumps were primarily selected from two sources. First was the product portfolio of Hangzhou Qinjie Electromechanical Co. Ltd., which offers low-power DC solar pumps [52]. Second was the product portfolio of Taizhou Qingquan Pump Co. Ltd., which offers higher-power AC pumps [106]. Referencing the reported specifications of selected pump models, pump efficiency η_{pump}, pump price C_{pump} (assumed equal to the single unit price listed on Alibaba.com), and pump lifetime (assumed equal to the pump warranty) were incorporated into the system cost estimations. The pump pricing was based on the manufacturers' high volume (>50 pieces) listing prices, excluding shipping fees. The efficiencies of the selected pumps were obtained from the manufacturer's efficiency testing data.

For PV-powered systems, the power P [W] needed to reach a desired operating point was calculated using

$$P = \frac{\rho_w g Q h_{tot}}{3600 \eta_{pump}}, \tag{2.3}$$

where ρ_w is the density of water and g is the acceleration due to gravity.

For systems using grid electricity or fuel, the daily energy E_{daily} [MJ] needed to meet the irrigation demand was calculated using

$$E_{daily} = \frac{\rho_w g Q h_{tot} t_{irr}}{3600 \eta_{pump}}. \tag{2.4}$$

The systems' capital costs C_{cap} [USD] were estimated using pump costs, irrigation equipment costs, and power costs (if applicable) using

$$C_{cap} = C_{pump} + A_{field} C_{equip \ \ per \ area} + P C_{Watt}. \tag{2.5}$$

Irrigation equipment cost included the upfront cost to the farmer of equipment necessary to carry out the irrigation strategy, such as hoses, field pipes, sprinklers, or drip lines, but it excluded the cost of installation, training, water source access, and pipes from the water source to the pump.

The systems' operating costs C_{op} [USD] were estimated using applicable energy costs and

$$C_{op} = t_{eval} \left(365 E_{daily} C_{MJ} + \sum_{component} \left(\frac{C_{rep.}}{LT_{equip}} \right) \right), \tag{2.6}$$

where t_{eval} is the evaluation time period set by each market segment's needs, $C_{rep.}$ is any component replacement costs (equal to their capital costs), and LT_{equip} is the corresponding equipment's expected lifetime. The operating costs included the cost of electricity or fuel to transport water from the source to the crops but excluded the cost of hired labor.

This first-order analysis assumes that the power is constant over the duration of the irrigation event. This assumption is generally valid for grid-powered and fuel-based sources, but less so for PV-powered. However, this analysis still gives an estimate of the order of magnitude cost expected for a given irrigation strategy. Excluding hired labor costs is another limitation of this analysis. Labor can be one of the larger operating costs for farmers but is outside the scope of this feasibility analysis. Labor is instead evaluated qualitatively when considering users' needs. Additionally, the costs of the tanks, batteries, filters, and fertigation units were neglected for these calculations because they are relatively small in cost or because they are not as sensitive to changing irrigation strategies.

Some inputs to this model depend on irrigation needs from different market segments, including the area irrigated, the daily irrigation time, the depth of a borehole or well, and the crop water requirement (Table 2.1). Other inputs to this model are independent of market segments, including the irrigation equipment cost per hectare, the equipment lifetime, the equipment operating pressure, the water factor of an irrigation method, and the cost of energy sources (Tables 2.2-2.4). The values used for these inputs were gleaned from literature and interviews with distributors on their current offerings. If citations are not provided in these tables, interview data and justifications are presented in Appendix C.

The irrigation methods and energy sources in Tables 2.3 and 2.4 were selected because they are commonly used throughout EA or because they are emerging strategies

Table 2.2: Crop water requirement parameters used as inputs for the technical and economic feasibility model [62].

	Crop water requirement W_c
Medium (cabbage is representative)	5 mm/day
High (tomato is representative)	7 mm/day

that are not widely used but have the potential to create an impact in the region if introduced at scale. Combining data from interviews and literature, four irrigation methods, one emerging irrigation method, and three common energy sources were selected. The considered irrigation methods were:

- Manual irrigation: Using buckets or handheld hoses to deliver water to the field
- Flood or furrow irrigation: Covering the entire field with water or filling furrows between crop beds with water, respectively
- Butterfly sprinklers: For this analysis, it is assumed that a farmer uses one set of five sprinklers that they move throughout their field every 30 to 60 minutes
- Non-pressure compensating (NPC) inline drip irrigation: Drip irrigation works by delivering water to rows of crops through a network of stationary main and submain pipes and lateral lines. The emitters within the lateral lines do not compensate for pressure changes expected in a pipe network, so the flow can be non-uniform
- Low-energy pressure-compensating (LE PC) inline drip irrigation: PC drip emitters regulate their flow rates given the pressure changes expected in a pipe network, so flow is uniform throughout the field. LE PC drip is an emerging technology developed by the MIT Global Engineering and Research (GEAR) Lab. LE PC emitters activate at lower pressures than conventional PC emitters,

giving them the potential to save 42–54% in pumping power, an attribute that has shown promise in EA [102, 114].

The considered energy sources were:

- Photovoltaic (PV) panels
- Grid electricity
- Fuel (e.g., diesel or petrol).

Details of these irrigation methods and energy sources, as well as relevant citations and justifications for why they were selected, are in Appendix C.

Table 2.3: Irrigation method parameters used as inputs for the technical and economic feasibility model.

	Equipment cost [USD/ha] $C_{equip\ per\ area}$, $C_{rep.}$	**Equipment lifetime [years]** LT_{equip}	**Operating pressure [m]** h_{equip}	**Water factor** f_w
Manual irrigation	50	2	1	0.5
Floor or furrow irrigation	25	2	1	1.0
Butterfly sprinklers	26.5	2	10	1.0
NPC drip subsections	2400	3	14	0.5
LE PC drip subsections	6000	10	5.9	0.5

2.3.2 Candidate irrigation systems for each market segment and their estimated costs

Irrigation methods and energy sources were next assessed for their fit for each market segment based on the segment's specific user-driven irrigation needs and value propositions from Table 2.1. An irrigation method or an energy source was assumed to be a

Table 2.4: Energy source parameters used as inputs for the technical and economic feasibility model.

	Cost C_{Watt}, C_{MJ}	**Equipment lifetime [years]** LT_{equip}
PV panels	0.81 USD/W	20
Grid electricity	0.06 USD/MJ	N/A
Fuel	0.03 USD/MJ	N/A

candidate unless there was a user need or value that suggested it was a non-candidate. Table 2.5 presents the candidate and non-candidate irrigation methods and energy sources. In the case of a non-candidate method or source, a justification is given.

Using inputs from Tables 2.1-2.4, Equations 2.5 and 2.6 were used to estimate the system costs of candidate irrigation strategies. Figure 2-1 shows, for each market segment, the five candidate systems with the lowest lifetime costs and the corresponding estimated capital and operating costs. For both smallholder markets, there were not five candidate irrigation strategies, so fewer than five are shown. In all four market segments, PV panel-based systems had the lowest lifetime costs, followed by fuel and grid-based systems, respectively. In all segments, the PV panel- and LE PC drip-based systems had the highest capital costs. For medium-scale contract farmers and remote farmers who operate on a longer investment timeline than smallholders, the LE PC drip-based systems had lower lifetime costs than the NPC drip-based systems.

Table 2.5: Candidate and non-candidate irrigation methods and energy sources for each market segment, based on user-driven needs.

	Traditional smallholder	**Semi-commercial smallholder**	**Medium-scale contract farmer**	**Remote farm owner**
Manual irrigation	Candidate	Non-candidate. The time needed to manually irrigate 0.25 ha for 6 hrs/day is too high for a farmer who is growing their business.	Non-candidate. The irrigated areas of 2-5 ha are too large for this irrigation method.	Non-candidate. The irrigated areas of 1-4 ha are too large for this irrigation method.
Flood or furrow irrigation	Candidate	Candidate	Non-candidate. Crop uniformity is important for resale value in this segment, and this method does not ensure uniformity.	Non-candidate. Crop uniformity is important for resale value in this segment, and this method does not ensure uniformity.
Butterfly sprinkler irrigation	Candidate	Candidate	Non-candidate. The irrigated areas of 2-5 ha are too large for this irrigation method.	Non-candidate. The irrigated areas of 1-4 ha are too large for this irrigation method.
Drip irrigation (NPC or PC)	Non-candidate. Farmers lack the amount of training needed to use drip effectively.[a]	Candidate[b]	Candidate	Candidate
PV panels	Candidate	Candidate	Candidate	Candidate
Grid electricity	Non-candidate. Farms are too rural to have reliable connections.[c]	Non-candidate. Farms are too rural to have reliable connections.[c]	Candidate	Candidate
Fuel	Non-candidate. High and fluctuating costs of fuel is a crutch in farmers' budgeting. Fuel can also be difficult to source.[d]	Non-candidate. High and fluctuating costs of fuel is a crutch in farmers' budgeting. Fuel can also be difficult to source.[d]	Candidate	Candidate

One stakeholder who sells irrigation equipment in Ethiopia says that farmers need 5+ years of training before they can use drip effectively. Another stakeholder from an NGO said he has seen inexperienced farmers using drip lines as fencing or to tie up cattle. This happened because the farmers did not have the experience level necessary to use drip technology properly, and we have shown the challenge of disseminating this information to rural communities.

Unlike traditional smallholders, many semi-commercial smallholders have more access to professional training, so both NPC and LE PC drip irrigation are feasible methods for this market segment.

Farms for these two market segments are too rural to have reliable connections. [14]

Several interviewed farmers conveyed that the high and fluctuating cost of fuel was a crutch in their monthly budgeting. While fuel is currently the most common energy source for the minority of smallholders who have graduated from manual or rainfed irrigation, given its observed drawbacks, this work assumes that fuel is not a realistic energy source for the majority of traditional smallholders

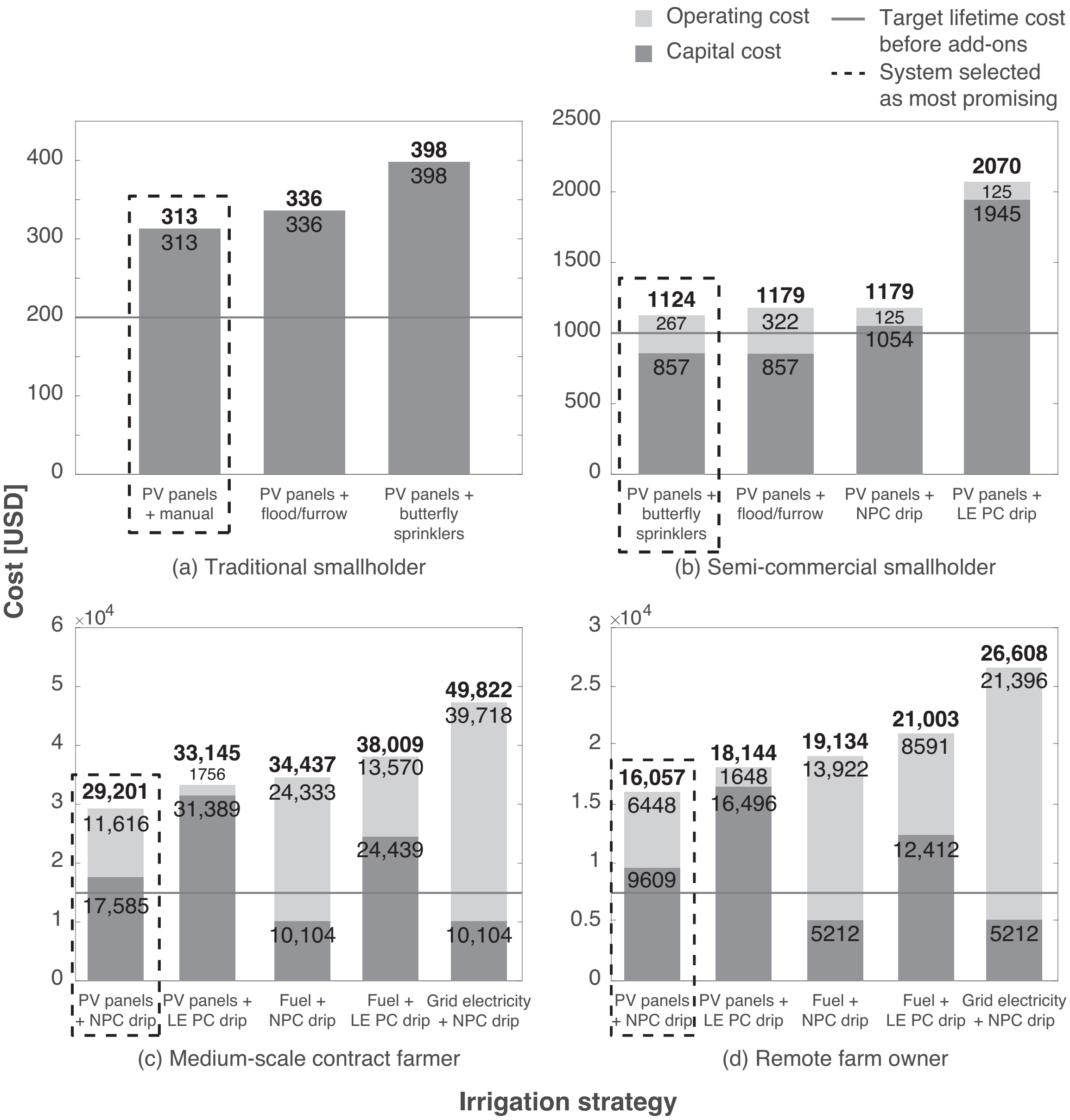


Figure 2-1: Estimated system lifetime, capital, and operating costs for candidate irrigation strategies, ranked by lowest lifetime cost, for (a) traditional smallholders, (b) semi-commercial smallholders, (c) medium-scale contract farmers, and (d) remote farmers

2.3.3 Discussion of opportunities to deliver on value propositions and irrigation needs

Synthesizing results about farmer needs and values (Table 2.1), farmer risk adverseness (subsections 2.2.2-2.2.2), and estimated system costs (Figure 2-1), the most promising irrigation strategy was chosen for each market segment (boxed irrigation strategies in Figure 2-1). These most promising strategies were selected because they were most likely to deliver on that segment's value propositions and irrigation needs. On a case-by-case basis, the insights about user needs and value propositions were weighed with the results of estimated system costs. This method, detailed in the following paragraphs, allowed for a holistic view when selecting promising new irrigation systems for EA farmers because it factored in both user-driven requirements as well as technical limitations. The results give high-level design requirements of irrigation systems that could deliver higher value to farmers than existing systems do (Table 2.6).

The system flow rate, system pressure head, and estimated costs were determined during the technical and economic feasibility analysis. The maximum pump diameter is based on the water source available to farmers in that segment, and the system lifetime is based on the investment timescale of each market segment. The target selected lifetime cost is repeated from Table 2.1. Because value add-ons (e.g., home lighting, cell phone charging, and small appliances) were not considered in the feasibility analysis, they are not repeated here, but they would be important for irrigation engineers to incorporate in system designs.

While no systems meet the traditional smallholder's target lifetime cost, the most promising system for this market segment uses PV panels + manual irrigation. This 313 USD system has the lowest lifetime and capital costs of all candidate systems. PV panels, which have no operating costs, were the only power source available to this market segment. There are no foreseen equipment replacements needs in the 1-year timescale for which the traditional smallholder plans. The irrigation strategy used for this system is water-saving, so this has the potential to be a sustainable solution. To serve their daily irrigation needs, this system would operate at 0.8 m^3/hr at a pressure head of 11 m. Pumps should be $<$15 cm in diameter to fit in hand-dug wells.

For the three remaining market segments, pumps should all be $<$10 cm in diameter to fit in 4-inch boreholes, which stakeholders agreed was a standard size for boreholes in EA.

Table 2.6: Summary of most promising opportunities for irrigation systems and their corresponding technical requirements.

	Traditional smallholder	**Semi-commercial smallholder**	**Medium-scale contract farmer**	**Remote farm owner**
Irrigation strategy	PV panels + manual irrigation	PV panels + butterfly sprinklers	PV panels + NPC drip irrigation	PV panels + NPC drip irrigation
System flow rate [$\mathbf{m^3/hr}$]	0.8	2.9	20	10
System pressure head [m]	11	35	114	114
Maximum pump diameter [cm]	15 cm	10 cm	10 cm	10 cm
Minimum lifetime [years]	1	3	5	5
Estimated system costs [USD]	Capital: 313 Operating: 0 Lifetime: 313	Capital: 857 Operating: 267 Lifetime: 1124	Capital: 17,585 Operating: 11,616 Lifetime: 29,201	Capital: 9609 Operating: 6448 Lifetime: 16,057
Target system lifetime costs [USD]	300 USD; 200 USD before value add-ons	1300 USD; 1000 USD before value add-ons	18,000 USD; 15,000 USD before value add-ons	9000 USD; 7500 USD before value add-ons

The most promising system for semi-commercial smallholders uses PV panels + butterfly sprinklers as the irrigation strategy. At 1124 USD, the system for this irrigation strategy has the lowest estimated lifetime cost. It has an estimated capital cost equal to the PV panel + flood/furrow system, but a lower operating cost. There are no user-driven needs that would justify selecting the flood/furrow system over the butterfly sprinkler system. Flood/furrow irrigation takes significant labor to prepare the field while butterfly sprinklers take minimal, ongoing labor to move the sprinklers throughout the field each day. The PV panel + NPC drip system has a similar lifetime cost to the PV panel + sprinkler. However, the 23% higher capital cost of this system would likely not be convincing to semi-commercial smallholders who are very sensitive to high capital costs.

Medium-scale contract farmers' most promising irrigation system uses PV panels + NPC drip irrigation. These farmers value the potential profit an irrigation system could deliver, and this irrigation strategy leads to a system with the lowest estimated lifetime cost. While the fuel + NPC drip has appeal for its low capital cost (43% lower than PV panels + NPC drip), it has an 18% higher lifetime cost. For medium-scale contract farmers who are able to afford the capital investment, the PV panels + NPC drip system is most suitable. As shown in subsection 2.2, farmers in this segment have seen past success in farming, so they have likely built some capital and they are less risk-averse than smallholders. This makes them likely to adopt the higher capital, but lower lifetime cost system that uses PV panels + NPC drip irrigation. To serve the irrigation needs evaluated in this work, the system would need to operate at 20 m^3/hr and 114 m of pressure head. This system would also need to be flexible for the wide range of farm characteristics found in this market.

A system using PV panel + NPC drip irrigation would serve the remote farm owner segment best. The justification for this selection parallels that of the medium-scale contract farmer. Further, remote farm owners would value the increased weather data that a PV panel-based system could also benefit from. Owners in this segment value more advanced technology, and PV panels deliver this over diesel or petrol. PV panels do not need the same amount of labor input as a fuel-based system would, so this system could alleviate some labor concerns that remote farm owners have. The system would need to operate at a 10 m^3/hr flow rate and 114 m pressure head to meet the irrigation needs analyzed in this chapter.

2.4 Discussion

In all four market segments, the estimated system costs do not meet the target costs (Table 2.6), highlighting areas for future technological innovation. There are a number of ways that these costs could lower. First, longer-lasting or less expensive pumps would decrease the system costs. Selected pumps had one- or two-year warranties, meaning a farmer would need to replace them several times during a system's lifetime. More expensive, longer-lasting pumps are available from manufacturers like Xylem and Grundfos, but they are seldom chosen by farmers in these segments. Instead, the low capital costs of the pumps used in this analysis make them the most popular options. The results show a need to increase the lifetimes of low-cost pumps or decrease the costs of long-lasting pumps.

A second identified area for technical innovation is to optimize the design of an irrigation system. Once a promising irrigation strategy is selected (as shown in this work), a systems-level model that incorporates key farm parameters, local weather data, and locally-available system components could help irrigation engineers design systems that are optimal for a given farm's case. This design strategy could help lower operating and capital costs because the system is not over- or undersized for that particular farm's needs. A model developed by the MIT GEAR Lab has begun to address this opportunity for innovation [96, 49].

Developing longer-lasting and less expensive drip equipment would be an innovation that benefits the EA irrigation market. LE PC drip equipment has a 10-year lifetime but high capital cost, making it unavailable to many farmers in EA. NPC drip equipment has a lower capital cost but has a 3-year lifetime. One possible method to reduce drip system costs while increasing system lifetime is to consider the thickness of drip line walls, or lateral walls. According to interviews with drip irrigation manufacturing engineers, a large component of the product cost is due to the lateral line wall material. This wall thickness is proportional to both the equipment cost and its lifetime. If innovation of new wall materials could increase lifetimes without increasing costs, it would add value to both medium-scale contract farmers and remote farm owners in EA.

Technical innovation is also needed in the design of anti- or low-clogging emitters. Farmers and stakeholders claimed that clogging of emitters is a large drawback to the technology. Stakeholders involved in distributing irrigation equipment have seen drip disadoption because of clogged emitters. Innovation in this space might lower the training threshold needed for effective drip use.

Further opportunities for innovation come when assessing the value add-ons in Table 2.1. For the traditional smallholder, this is a system that enables phone charging and home lighting. The technology to do this exists but has not been bundled with an irrigation system geared toward this market yet. For the semi-commercial smallholder, this may mean a system that powers small home appliances. SunCulture's ClimateSmart™ with Battery systems do pair with some appliances, and this helped the company better serve its customer base. However, there remains an opportunity to expand the available options. For medium-scale contract farmers and remote farm owners, value is added when systems can be flexible based on farm parameters. One potential opportunity to address this is a central controller that can be paired with different equipment (pumps, for example) and operate at the most efficient point based on a particular farm's characteristics. This controller could integrate with low-cost sensors to provide a farmer with predictive insights on how to manage their farm.

Policy or business innovation is always an alternative path to make system costs match performance needs. Government subsidies, sponsorship programs, or loan programs are some ways to increase the adoption of irrigation systems without farmers paying the full price when they are unable or unwilling. Further reaching and improved extension services could help teach farmers the value these systems could bring to their farms, increasing the amount farmers are willing to pay for irrigation systems. In the case of remote farm owners, increased sensors alone may not provide them with the confidence they want. They might additionally benefit from professional farm management services that ensure quality labor when owners are not on site.

This analysis sought to characterize the performance requirements to meet the needs of the majority of each market segment. Within each segment, there will be variation in farmers' willingness and ability to pay, so there will be some percentage of farmers who are willing and able to pay more for a system than the target costs in Table 2.1. The promising systems identified in this work would not need further innovation to serve this minority of farmers. Irrigation equipment designers can use the technical specifications presented in this thesis to reach this minority of farmers now while they wait for further research and development.

This analysis did not consider combinations of strategies, meaning two irrigation strategies used by the same farmer. However, that might be valuable to some farmers, particularly the semi-commercial smallholder who values an irrigation system that helps them grow their businesses and lifestyles. One benefit of the concluded PV panel + sprinkler system is that the selected pump could allow farmers to expand their fields once they are able to invest in drip irrigation. The 0.25 ha field of butterfly sprinklers in this analysis needs a flow rate of 2.9 m3/hr and a pressure of 35 m. An expanded 0.5 ha field of NPC drip irrigation operates at the same flow rate and 39 m of head. The selected pump could serve both of these flow rates with an additional 216 USD of PV panels added when a drip network is installed. The highest costs of this system are the pump and PV panels (99% of the original capital cost), so farmers would not need to reinvest in that equipment. This feature serves the semi-commercial smallholder's need to expand their farming business. Further analysis of this growth strategy could highlight additional areas for innovation.

One limitation of this work is the relatively small number of farmer interviews conducted: 33. The authors chose to conduct fewer, more in-depth interviews to best assess the values of recruited farmers. These interviews were supplemented with stakeholder interviews and literature that could provide data from a more representative sample. As technical innovations are pursued, continued engagement with farmers and stakeholders will be crucial to continue answering the questions asked in this work.

A second limitation of this work is that pump warranties were used to represent their lifetimes. In reality, a pump with a two-year warranty might last five years, but these data are not well documented by pump manufacturers or distributors so could not be used. A manufacturer's warranty reflects their confidence in the equipment's lifetime, so this was assumed to be an adequate substitute for pump lifetime. In the case of the medium-scale contract farmer, the manufacturer gives a one-year warranty, so 16% of a farmer's estimated operating costs (3528 USD) is due to annual pump replacements. If pumps in fact lasted longer than one year (as did the pumps of interviewed farmers), irrigation system costs would be closer to the targets identified in this work.

A final limitation of this work was that farmers' and laborers' time was not assessed in the cost of the systems. Farmers with diversified income sources have an opportunity cost when they spend multiple hours per day on the farm. Farmers who hire laborers must pay these workers, adding to their operating costs. These unaddressed costs could influence which irrigation strategy is most promising for a given market segment. If traditional smallholders have high opportunity costs, they may value a manual irrigation-based system less than this work concludes because they may not want to spend the time it takes to manually irrigate their farm. Instead, a flood- or furrow-based system may provide this segment the most value. The remote farm owners and the medium-scale contract farmers are most likely to have laborer wages as part of their operating costs. Including labor costs in the analysis is unlikely to change the conclusion that PV panels + NPC drip-based systems are the most promising systems for these segments because all systems shown in Figures 1c and 1d would have similar additional labor costs. However, the expected operating costs in these cases will be higher, potentially decreasing the number of farmers willing and able to adopt these systems. In this analysis, time-related costs were assessed qualitatively through interviews, but a quantitative measure would be helpful. Despite these limitations, the process followed in this work could be applied to other global regions where there is a need to increase the adoption of irrigation systems.

The results presented in this work could provide value to farmers and other stakeholders in the EA irrigation market in several key ways. The sets of irrigation product requirements produced can guide irrigation equipment designers as they innovate. Irrigation companies and NGOs can benefit from new markets that are discovered through the market segmentation. Farmers in new and existing markets could benefit from irrigation products designed specifically for them, increasing their likelihood of adoption. Increased adoption and use of irrigation products could contribute to the growing need for food production in EA. Many designers working in global contexts design for users who are underserved by existing products, so the process followed here is valuable for researchers working in similar regions. In those contexts, this process can be repeated to assess relevant market segments and elucidate areas for further innovation.

2.5 Conclusions

The aim of this study was to identify new opportunities to enhance the adoption of irrigation systems in EA by elucidating and targeting the needs of distinct market segments. Within the range of farmers who cultivate $\leq$5 ha, four market segments—the traditional smallholder, the semi-commercial smallholder, the medium-scale contract farmer, and the remote farm owner—and their corresponding needs were elucidated. Informed by farmer and stakeholder interviews, value propositions for irrigation systems that could meet those needs were built. A techno-economic analysis was used to estimate the costs of irrigation systems that could meet farmers' irrigation needs. By combining results from this two-part analysis, opportunities for developing irrigation systems that could increase irrigation adoption in EA were found for each market segment. In the traditional smallholder market, this work found an opportunity for a system that uses PV panels + manual irrigation. For the semi-commercial smallholder, a PV panel + butterfly sprinkler-based system is a promising area of opportunity. Finally, medium-scale contract farmers and remote farm owners would find the most value in a PV panel + NPC drip-based system.

The results show that none of these systems are expected to be low-cost enough to meet the price and performance needs of small- to medium-scale farmers in EA. However, the results do show opportunities where technical innovation can happen in order to serve these markets. One opportunity is for the design of lower-cost, longer-lasting pumps than currently exist. A second opportunity is for the development of lower-cost, longer-lasting NPC or LE PC drip lines. Anti- or low-clogging NPC or LE PC drip emitters would help increase the adoption of drip technology in EA. For the semi-commercial smallholder, there is a potential need to design a system that allows the farmer to expand their irrigated area without purchasing a completely new system. This work shows a farmer could irrigate 0.25 ha with butterfly sprinklers or 0.5 ha with NPC drip irrigation while using the same pump and PV panels. This system architecture would allow the farmer to invest in a new irrigation method without investing in an entirely new system.

Opportunities exist to design irrigation systems that fulfill the values of farmers beyond their irrigation needs alone. For the traditional smallholder, this means a system that provides phone charging and home lighting. For the semi-commercial smallholder, a system that enables small home appliances. The medium-scale contract farmer and remote farm owner would benefit from low-cost data and prediction tools that support their farm management. The remote farm owner would also benefit from tools that help them ensure the quality of care their crops receive when they are off-site. The remote farm owner segment is an emerging one, so further needs can be discovered once more farmers enter this space. Future work will move towards realizing these innovations, continuing to engage farmers and market stakeholders as prototypes of systems and sub-components are built.

Chapter 3

Design and Evaluation of an Automatic Scheduling-Manual Operation (AS-MO) User Experience Aimed at Bringing Precision Irrigation to Resource-Constrained Farmers

3.1 Introduction

The aim of this chapter is to propose and evaluate a means of bringing many of the water and energy efficiency benefits of precision irrigation to resource-constrained regions without the high equipment costs and complexity of existing methods.

The United Nations' second Sustainable Development Goal (SDG 2) calls for the achievement of food security by 2030 [112]. This aim is particularly imperative in low- and middle-income regions such as East Africa (EA) and the Middle East and North Africa (MENA), where over 33% and 10% of the population, respectively, is projected to be undernourished in 2030 [36]. Numerous studies have shown that increasing access to irrigation is an effective path to achieve food security in these regions [10, 95, 83]; however, irrigation is a water- and energy-intensive process, counter to the additional aim of SDG 2 to promote sustainable agriculture. The high water use of irrigation is particularly challenging in arid and semi-arid regions like MENA and EA, respectively. In EA, as described in Chapter 2, these farms, generally sized 5–15 acres, rely on hired manual labor to feed the growing city centers [59]. In MENA, the farm size scale is country-dependent, with small-scale farms generally ranging from 5–25 acres and medium-scale farms generally ranging from 50–120 acres [115, 47]. Both small- and medium-scale farms typically rely on hired manual labor, but medium-scale farms may also have specialized labor such as a farm manager or agronomist. The growing number of small- and medium-scale farms has the promise to increase food security in EA and MENA, but doing so sustainably remains a challenge [60, 122].

Solar-powered drip irrigation has been proposed for regions with high solar irradiance as a means to increase yields while reducing water and fossil fuel use [94, 53, 8]. Drip irrigation uses a network of pipes and emitters to deliver water directly to the crops' root zone, saving up to 50% of water compared to flood irrigation, a commonly-used method [9]. Drip irrigation can improve overall energy efficiency by reducing the total water volume delivered to the field, thereby reducing the total pumping energy; this energy saving is particularly impactful on farms that irrigate from deep boreholes. Solar power is a sustainable option that is especially applicable in rural EA where access to grid electricity can be uncommon [14] and in arid, water-stressed regions, like MENA, that have high solar irradiance [125, 43, 124]. However, as noted in Chapter 2, solar-powered systems have high investment costs that can dominate the system cost [115] or be a significant barrier to adoption by farmers. System energy use is critical in off-grid irrigation because it dictates the cost of the solar array and any energy storage options such as water tanks or batteries.

Prior work has suggested that water- and energy-saving technologies could particularly benefit medium-scale farms in EA and small- to medium-scale farms in MENA, many of which have access to capital to pay for some of this technology [115, 47].

However, irrigation technologies can only conserve resources when they are properly operated and maintained at the farm-level. Research has shown that farmers' practices do not necessarily result in ideal irrigation, which is in part due to a lack of technical training, and in part due to farmers, understandably, prioritizing risk mitigation over introducing new sustainability practices [12, 48].

Precision irrigation, the practice of calculating and delivering the correct amount of water to crops at the correct time, could help resource-constrained farmers realize the water and energy savings of solar-powered drip irrigation. Precision irrigation technologies measure farm and weather conditions and calculate ideal irrigation schedules, often using automated valves to carry out these schedules [2, 103, 40]. The implementation of precision irrigation control for solar-powered drip systems is an active area of research. The aim is to improve water use efficiency—the ratio of crop demand to water applied—and improve solar energy use efficiency as a way to reduce power system cost [2, 25, 18]. Previous studies have proposed ways to adjust irrigation in real-time using either retroactive agronomy measurements or predictive modeling [1, 23], optimize irrigation schedules for minimal water use [71], and match the irrigation power requirement to the available solar power profile—a process the authors of the present study have termed “profile-matching" [130, 74].

Despite demonstrating water and energy saving capabilities, these studies focused on individual cases and did not examine how farm heterogeneity would impact solution scalability. Furthermore, existing precision irrigation solutions and those proposed in literature are largely inaccessible to the target user groups of this study. In literature, the proposed precision control solutions often require technical expertise to calibrate and operate. These solutions assume that network connectivity, sensing and electronics hardware, and computing power are all financially and physically accessible to the end user, which may not be the case. Many existing precision irrigation controllers rely on arrays of sensors, solenoid valves, and proprietary hardware and software [128, 74, 130, 5], which cost up to tens of thousands of dollars to equip an entire medium-scale farm [116].

The economic constraints in EA and MENA make it difficult for medium-scale farmers to adopt existing precision irrigation technologies. As found in Chapter 2, these farms often employ local laborers to both monitor and carry out irrigation tasks using manual valves [115]. These laborers use inexpensive but time-consuming and often imprecise manual methods for determining when to irrigate, like “stick” and “ball” tests [116]. In a stick test, a laborer inserts a stick 10 cm into the soil. If it comes out with dirt attached, the soil is moist enough. In a ball test, a farmer forms a handful of dirt into a ball. If the ball crumbles when let go, the soil is too dry. The irrigation experience of hired laborers varies widely, so farmers cannot rely on these binary tests to deliver the most water- and energy-efficient irrigation. While human laborers can make observations of current and past weather and crop conditions, they cannot make accurate, detailed forecasts such as those used in precision irrigation. In addition, relying on past conditions alone does not account for changes in climactic conditions as global temperatures rise [98, 123]. Inaccurate forecasting of weather conditions can negatively impact the reliability of solar-powered irrigation systems on cloudy days if farms have not properly planned for future weather events.

Some existing products attempt to bridge the gap between fully automated precision irrigation and fully manual heuristic methods. However, these products are timer-based and largely fall short of delivering the efficiency and prediction benefits of precision irrigation. As two examples, the Pro-C irrigation controller (Hunter Industries, California) and the SST1200OUT irrigation timer (Rain Bird Corporation, California) are relatively low-cost products—in the $100–300 range—that control a series of solenoid valves to carry out predetermined irrigation schedules. While these products are affordable to many farms, they still rely on the farmer to determine and input the irrigation schedule. Even for the most experienced farmers, it is extremely challenging to determine an irrigation schedule that concurrently optimizes water and energy use—tasks often accomplished by precision irrigation systems. In addition, these devices cannot deliver the computationally-intensive benefits of conventional precision irrigation. As an improvement, a Solar Sync rain sensor (Hunter Industries, California) can be connected to the Pro-C controller to end irrigation events early if rain is sensed. However, this small modification does not integrate the full prediction, optimization, and efficiency benefits that precision irrigation systems have demonstrated for higher-resourced markets.

There is a need to understand and define the functional requirements of a precision irrigation tool, and its associated user experience (UX), specifically for resource-constrained contexts that enables farmers to access the benefits of solar-powered drip irrigation. In this chapter, we define UX as how a user interacts with the irrigation tool. Figure 3-1 characterizes two of the critical actions of irrigation system control. The first looks at determining a schedule of irrigation events (e.g., "Scheduling"), and the second at operating valves in a hydraulic network (e.g., "Operation"). Each of these actions can be done either manually by a farmer or automatically by the system, resulting in four distinct design spaces. Fully automated precision irrigation systems are in the lower right quadrant, while fully manual methods, like stick or ball tests paired manual valves, are in the upper left. Existing irrigation timers fall into the manual scheduling and automatic operation quadrant. To the authors' knowledge, no commercial technologies exist that can deliver the automatic scheduling benefits of precision irrigation to farms that primarily rely on the manual operation of valves, such as the resource-constrained farms in EA and MENA. The lower left quadrant of Figure 3-1 highlights this gap in the design space.

We hypothesize that a technology in the automatic scheduling and manual operation (AS-MO) design space is well-suited for the small- to medium-scale farmers typically found in EA and MENA. This tool could incorporate proposed techniques from literature to improve solar-powered drip system operation, in particular, minimizing water use and using profile-matching to improve energy use efficiency and reduce power system cost. This AS-MO approach could increase water use efficiency at the farm level, reduce costs, and provide farmers with real-time feedback and information about their systems, while also integrating easily with existing labor practices and leveraging farmer expertise.

A technology's potential impact relies on its adoption among target users. Adoption of irrigation technologies is particularly challenging in resource-constrained regions, with multiple examples of promising technologies not penetrating markets as

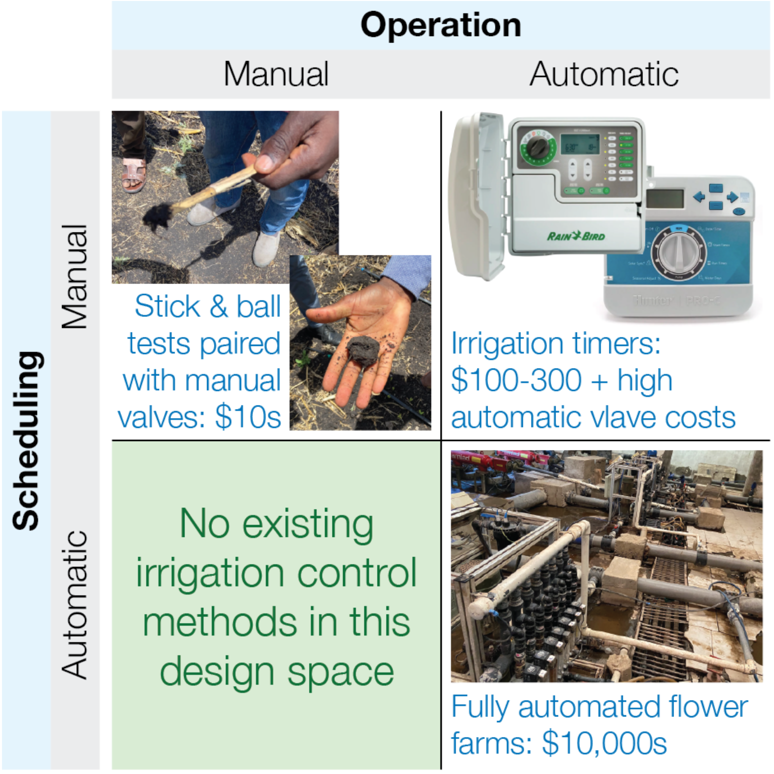


Figure 3-1: Visualization of the design space of irrigation system control methods with regard to two key elements: scheduling and operating. Existing methods typically fill three of the four design spaces. This work proposed a tool to fill the gap in the automatic scheduling and manual operation space. This work evaluates this design concept's fitness for medium-scale farmers in EA and MENA against existing solutions that use other control methods.

expected [121, 107, 79, 66, 4]. Farmers' desire to adopt an AS-MO tool in this context is unknown but critical to its potential to create an impact. To evaluate the potential viability of an AS-MO tool in the EA and MENA markets and to better understand how farmers might value and interact with such a tool in practice, this chapter addresses the following research aims:

1. Define the functional requirements of a precision irrigation tool for solar-powered drip systems in resource-constrained markets that integrates with the current practices and capabilities of target farms.

2. Characterize an AS-MO user experience (UX) architecture that meets these requirements to effectively transmit the benefits of precision irrigation to target users.

3. Substantiate the value of an AS-MO UX among potential users in EA and MENA markets and assess their desire to adopt a tool with this architecture, relying on storyboard-based interviews and focus groups.
4. Assess target farmers' satisfaction with the proposed AS-MO tool and UX and identify avenues for improvement.

The validation of the utility, ease of use, and value proposition of the AS-MO UX in this work will facilitate the creation of AS-MO irrigation tools that bring the benefits of precision irrigation to resource-constrained farms.

3.2 Functional requirements for precision irrigation in resource-constrained markets

Although the literature provides numerous ways to design and improve precision irrigation control schemes, the underlying assumption is that instrumentation complexity and cost are minor constraints to the end user. Conversely, in the case of resource-constrained markets, complexity and cost become key constraints on the design, which is perhaps why existing precision irrigation technologies are not widely adopted in these markets.

To meet the needs of target, resource-constrained users, a precision irrigation tool must deliver similar system performance to existing technologies, enabling small- and medium-scale farms to realize the benefits of solar-powered drip irrigation, while being technologically and financially accessible. Table 3.1 lists the functional requirements for such a tool to accomplish these tasks.

The third requirement in Table 3.1, describing an irrigation schedule that is shared with the user, is a noteworthy shift in the design ideology for precision irrigation equipment. Often, the goal for existing technologies is to drive towards full automation. In resource-constrained markets, however, it is often beneficial to keep the user in the control loop due to large variations in user technical experience and farm heterogeneity in terms of parameters such as crop type, local climate, field layout and

Table 3.1: Functional requirements for a precision irrigation tool that meets the needs of small- and medium-scale farmers in resource-constrained markets.

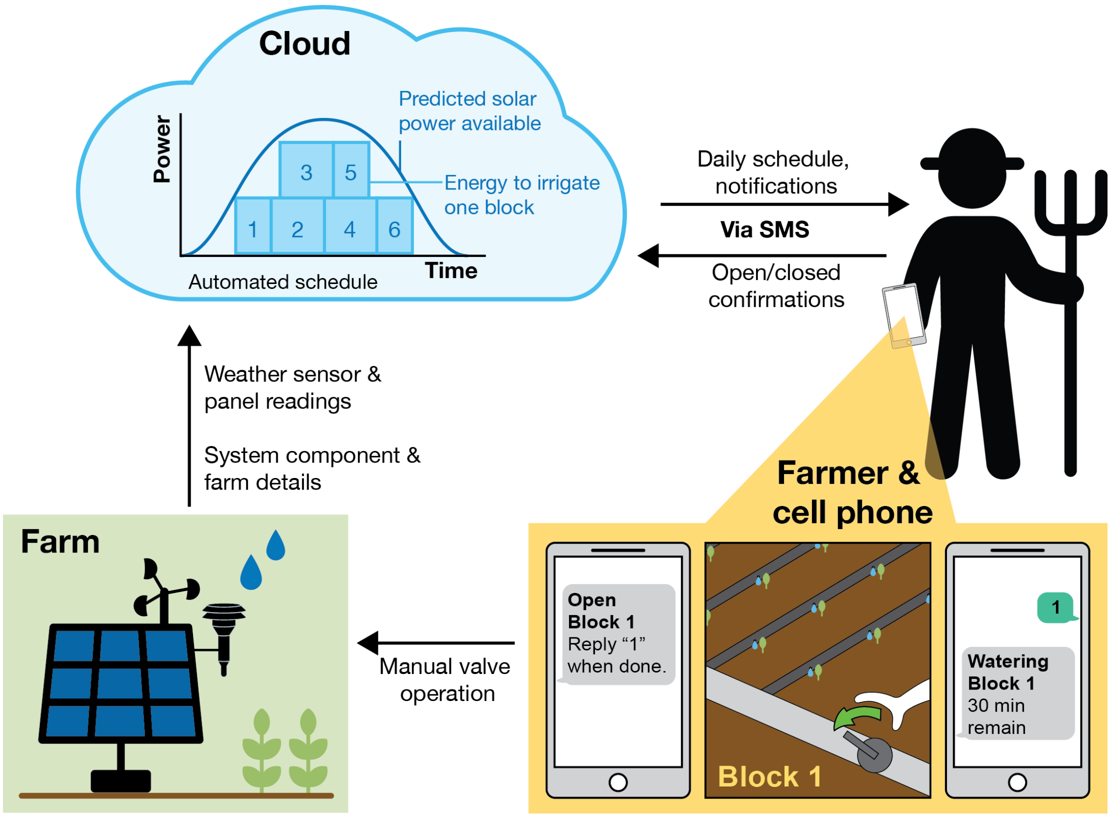
No.	Requirement	Elements	Justification
1	Improve system efficiency	Increase water use efficiency Increase energy efficiency (solar)	Deliver similar performance as existing precision irrigation tools, conserve resources, reduce costs
2	Case-specific	Scalable calibration procedure Easy-to-use data entry interface	Account for case-specific parameters (heterogeneity) on farms and varying levels of user experience
3	Create irrigation schedule and communicate with user	Intuitive user interface Non-disruptive communication frequency Compatible with local operating system	Eliminate need for expert technical knowledge, while building user proficiency by keeping them in the control/scheduling loop
4	Accurate irrigation amount	Accurate soil moisture estimation Accurate weather data/forecast	Mitigate risk to crop yield
5	Reliable operation	Reliable on-site connectivity Robust energy management/storage Robust calibration Simple maintenance Weatherproof	Mitigate risk to crop yield, make tool easy to maintain and promote adoption by building users' trust
6	Affordable	Low-cost (compared to existing tools) Minimal specialized hardware	Make tool financially and locally accessible to facilitate adoption

hydraulic equipment. Keeping the user in the loop may trade greater precision for less technical complexity, but this design decision allows the tool to leverage users' agricultural expertise and real-time human observation.

3.3 The proposed AS-MO tool and UX

An AS-MO tool for EA and MENA farms was conceptualized to meet the functional requirements described in Section 3.2. To facilitate automatic scheduling that improves system efficiency for these markets, the tool would integrate three key features found in the literature review: concurrent optimization of water and energy use, predictive modeling, and solar profile-matching. Current irrigation solutions optimize for either water or energy use. Considering both together has the potential to further reduce costs. Predictive modeling, as opposed to making retroactive adjustments to the schedule, would mean this tool can communicate a schedule to farmers ahead of time. Including profile-matching would increase system reliability on cloudy days and, according to previous research, has the potential to reduce the power system capacity by up to 50% without sacrificing reliability [130]. For the medium-scale Kenyan farm represented in Chapter 2, this translates to an estimated 20% life cycle cost reduction [115]. The top left of Figure 3-2 shows how the proposed theory could strategically coordinate irrigation events by predicting and then matching the pumping energy needed to meet crop water demand (light blue boxes) with the forecasted available power (dark blue line).

We chose to eliminate soil moisture sensors to minimize the use of additional, specialized hardware. Scheduling theories proposed in literature often require soil moisture sensors, which are expensive and complex to calibrate. The proposed tool could instead leverage cloud computing to build an optimal irrigation schedule and characterize soil moisture without the use of soil moisture sensors. It could do this using soil water balance calculations and several inputs from the farm [9, 26]. Farm inputs would include readings from several simple weather sensors, solar panel power readings, and user inputs regarding system component specifications and agronomy



Open Block 1 Reply "1" when done.

Watering Block 1 30 min remain

Figure 3-2: Depiction of the proposed AS-MO tool and UX. On the left, details about the farm and irrigation system are fed into an algorithm that leverages cloud computing and predictive modeling to automatically generate efficient irrigation schedules. On the right, this schedule is communicated to farmers for manual operation via SMS messages at the beginning of the day and at the start and end of each irrigation event. These messages instruct farmers to carry out the generated schedule by manually operating valves. When farmers confirm completed actions, they inform the algorithm how closely the schedule was followed so the next day's schedule can generate accordingly.

details, such as solar array capacity, pump operating points, irrigation block areas, crop types, and soil texture (lower left of Figure 3-2).

The right-hand side of Figure 3-2 shows how the AS-MO tool's UX would communicate a schedule that is easy for the user to follow. In its initial conceptualization, the tool sends Short Message Service (SMS) reminders throughout the day to farmers' cell phones, products which are increasingly more common in low-resource countries [24]. At the beginning of each day, the tool determines an irrigation schedule and presents it to the farmer. The farmer has the option to accept or slightly modify this preliminary schedule. Sending one message at the beginning of the day was a key design decision. It was hypothesized that this would help limit the frequency of interactions while still providing enough resolution for farmers to make efficiency-promoting changes to their irrigation practices. Once the accepted schedule begins, the tool sends additional messages to the farmer's phone, reminding them to manually open or close valves according to the schedule (lower right of Figure 3-2). The farmer would then manually open or close valves as directed and then send an SMS confirming the action was complete. Because farmers might not open or close a valve on time, a confirmation would allow the tool to measure how long each irrigation event was in practice without needing to use sensors throughout the field. This measurement is important for calculating the duration of future irrigation events. This interaction process is repeated throughout the day, according to the predetermined irrigation schedule.

The proposed AS-MO tool and UX meet the identified functional requirements for a precision irrigation technology for resource-constrained markets (Table 3.1). The scheduling theory targets optimal water and energy use efficiency in a solar-powered drip system (Requirement #1) and takes in site-specific details for calibration (Requirement #2). Cloud computing and predictive modeling are employed to ensure that the tool reliably delivers an appropriate amount of water (Requirements #4 and #5), and ensures that the hardware is affordable and easy to access and maintain (Requirement #6). Finally, the user experience is designed specifically for target farmers, employing SMS-based instructions that have proven successful in other fields (Requirement #3) [42, 88].

3.4 Initial AS-MO UX storyboard-based interviews and focus groups

3.4.1 UX storyboard-based interview methods

To understand how medium-scale EA farmers might value the proposed AS-MO UX on their farms, tours of 11 farms were conducted in October 2021 in Kenya. All of these farms fit the profile of a medium-scale EA farm, as described in Section 3.1. Tours were given by farm managers or employees and included on-site observations of existing solar-powered pumping systems, crop production techniques, and labor management practices.

To complement the farm tours, individual interviews and small focus groups were held with farm owners, managers, employees, and key market stakeholders, all of whom provided different perspectives on the AS-MO UX. These interviews and focus groups were facilitated using storyboards, tools that help engineers elicit user feedback on early-stage design concepts [117]. The low-fidelity nature of storyboards is appropriate for early design stages when the concept can change easily [111]. The four storyboards used in this study, provided in Appendix D, visually depicted:

1. How the proposed AS-MO tool might integrate into a farm with a solar-powered drip irrigation system. This was important so farmers could imagine using the tool on their farms.

2. The anticipated value the tool might deliver farmers in terms of energy, water, and cost savings. This visual compared anticipated farm operations without the tool to those with the tool, allowing farmers to see what might change.

3. How the tool integrates weather and agronomy details to build a schedule. Giving farmers a sense of how the tool worked could allow them to trust the automatic scheduling determination or say if a key input was missing.

4. How farmers interact with the tool on a daily basis. This visual allowed farmers to imagine the UX, so they could provide feedback on the interaction.

The storyboards were shown in the above order to progressively introduce more details and nuance about the product's features and potential benefits.

The storyboards were used to describe the AS-MO tool concept and UX along with guiding open-ended questions designed to understand the key benefits and costs the tool might have to the participant. Sample questions are provided in Appendix D. Throughout the interviews and focus groups, participants were asked to give both positive and negative feedback on the design concept. It was stressed that the tool and UX had not yet been commercialized and the features had not been solidified, highlighting that the participants' honest feedback would be critical to designing the most beneficial tool and UX. Participants were encouraged to ask questions about the design concept, highlighting what aspects concerned or confused them. To learn if farmers might adopt this technology, they were asked if they would consider installing the tool on their farm, and why or why not. If they answered "no," participants were asked if they would recommend the tool to a neighbor who was installing a new irrigation system on their farm, and why or why not. To continue developing the AS-MO design concept, farmers were asked if they had ideas for improving the tool or UX that should be considered.

Interviews and focus groups were conducted with 16 farm owners, managers, and employees, all associated with the 11 toured farms. These farmers were selected for the study because they were early adopters of solar-powered drip irrigation and/or potential lead users for the AS-MO tool. While lead users and early adopters may represent a small number of users, they often have the potential to provide unique and valuable insights on a piece of novel technology [113, 119]. Farmers who experiment with new irrigation techniques or agriculture equipment on their farms were considered lead users. Early adopters were farmers who had already been using more advanced irrigation methods than are typically utilized in EA, such as drip irrigation, solar-powered systems, or sensors on their farms [78, 28]. All interviewees had used these irrigation techniques for more than six months.

To complement farmers' responses and to learn if the proposed tool and UX could be a viable product in the region, 19 key market stakeholders who were broadly familiar with the EA irrigation market were also recruited for interviews. These stakeholders, whose roles and affiliations are given in Table 3.2, represented professional viewpoints of different sectors of the irrigation and agriculture markets. These individuals have collectively helped thousands of farmers improve their farms, so they could provide perspectives on a large population of farmers in ways that individual farmers could not.

Table 3.2: Roles and affiliations of the 19 market stakeholders interviewed in the initial portion of this study.

Role	**Affiliation**	**Affiliation description**	**Participant count**
Irrigation engineer	Davis & Shirtliff	An irrigation equipment distribution company serving EA	5
Manager	Davis & Shirtliff	An irrigation equipment distribution company serving EA	3
Manager	Xylem, Inc.	A global water solutions company; participants developed products for low- and middle-income countries (two focused on EA and the other on India)	3
Government official	Kajiado County	The local government in a county with a large agriculture sector	6
Borehole driller	Self-employed	Provides drilling services to farmers	1
Agronomist	Self-employed	Provides regular agriculture advice to farmers	1

Stakeholder interviewees were asked if they thought the proposed AS-MO tool could be a viable product, how they imagined that might happen, and what would need to change for this design concept to develop into a commercial product. Stakeholders were asked if a \$300–500 price range for the tool fit their price expectations. This estimated price point was based on the price point of individual timers in the manual scheduling-automatic operation design space [54, 90]. The proposed tool is expected to be slightly higher because several weather sensors are needed. These sensors are expected to be \$100–200, based on the price points of existing low-cost weather stations [19]. Like the farmers, the stakeholders were also encouraged to ask questions about and suggest changes to the tool and UX.

All study protocols were approved by the Massachusetts Institute of Technology Institutional Review Board (protocols E-3596 and E-4098).

3.4.2 Preliminary substantiation of value and market viability in Kenya

Fourteen out of 16 interviewed farmers claimed they would be willing to adopt the proposed AS-MO tool. They valued it for three key reasons related to automatic scheduling and the combination of automatic scheduling and manual operation.

First, farm managers, owners, and employees claimed that an automatic scheduling tool could increase the reliability of their irrigation. Thirteen out of 16 farmers reported challenges scheduling irrigation events during difficult-to-predict weather conditions, like cloudy periods. During these days, farmers said their systems had trouble pumping at desired rates. At the same time, a majority of participants made decisions about when to schedule irrigation events based on experience and observations at single points in time, not accounting for future events. A majority of participants were interested in the proposed tool's ability to predict the amount of solar power available and water needed. They claimed this feature could distribute and store water at rates that would reduce the risk to crops.

The second reason participants valued the proposed AS-MO tool is that they claimed that an automatic scheduling tool could increase their confidence while making irrigation decisions, saving them time and effort. Multiple farmers demonstrated manual tests, like the stick and ball tests, that they currently use to plan irrigation events. Multiple farmers noted that these methods were cumbersome because they needed to check multiple places in each irrigation block to assess water demand. Further, an agronomist noted that these binary tests do not account for the variation of soil textures and crop water requirements commonly seen between farms. This stakeholder claimed that the proposed tool could increase users' confidence in their irrigation schedules because it would account for these variations. Some farmers noted that they hire an agronomist to visit their farm every 1–2 weeks to provide irrigation scheduling advice, among other types of guidance. They claimed the tool could provide them with more frequent irrigation scheduling direction, further increasing their confidence in making irrigation decisions.

The third value farmers saw in the proposed AS-MO tool and UX was that it could enable more energy-efficient irrigation for a small investment and minimal hardware change. During eight out of 11 farm tours, energy inefficiencies in system operations were observed or noted by the farmers (e.g., a solar pump not running despite high solar irradiance). Farm owners recognized that pumping downtime either meant their solar system was oversized or that they were not irrigating to the farm's full potential, inefficiencies that were potentially costly. Participants believed that automatically-generated schedules could avoid these losses, and a majority preferred to realize this benefit while continuing to use manual valves over automatic ones. Farm managers and employees claimed they wanted to continue visually checking blocks at the end of irrigation events, suggesting a distrust in full automation. They also wanted to continue using the familiar hardware they currently use. Farm owners wanted to minimize the additional investment needed on the farm to gain several key benefits of automatic scheduling, so they preferred the less expensive option: manual valves.

There were two farmers who did not think they would adopt the tool. One owned the largest farm—15 acres—and claimed that automatic valves would be worth the investment on her farm. The other farmer was happy with her current farm practices and did not want to change them. It was expected that the tool may not meet the needs of all medium-scale EA farmers. However, the majority of farmers did value the tool, suggesting this design concept has the promise to become a valuable commercial product.

Farmers and key stakeholders claimed the proposed price point was appropriate for the anticipated efficiency benefits. When asked, farm owners said the estimated

$300–500 price point for the AS-MO tool matched their expectations. Several farmers reported paying an agronomist approximately $14/week for routine farm evaluations, further suggesting farmers' willingness to invest in irrigation advice. In all stakeholder interviews with equipment distributors, the price point estimate for the tool matched their expectations.

The interviewed stakeholders expressed their support for the AS-MO tool design concept to become a product in the EA market. At Davis & Shirtliff, all eight interviewed engineers and managers believed it was viable. A former director of this company said he was "convinced [this design concept] is feasible and can be implemented." At Xylem, Inc., all three interviewed managers agreed. They further believed this tool and UX could provide value to many of the resource-constrained regions they serve.

All other stakeholders—the agronomist, the borehole driller, or the government officials—expressed belief in the AS-MO tool's value to their customer base. The government officials mentioned that the market for solar-powered drip irrigation is expanding and an AS-MO tool could help farmers adopt good irrigation practices with their new systems. The borehole driller said that a tool that monitors irrigation events would help him advise farmers who are considering expanding irrigation on their farms. These preliminary results show that farmers in Kenya and stakeholders in EA value the *combination* of automatic scheduling *with* manual operation in the proposed tool and UX.

3.4.3 Design concept improvements based on preliminary storyboard interviews

Interviews and focus groups with farmers and stakeholders highlighted two key design changes to the proposed AS-MO concept. First, in the updated design, the tool sends messages using data rather than using SMS. Several farmers and stakeholders claimed that SMS rates were higher than data rates in Kenya, so it was preferred that the tool use data instead. As smartphone ownership and data coverage expand in both EA and MENA, this technology becomes more accessible to farmers, making it a viable alternative to SMS [127].

Second, the updated UX includes the ability for farmers to slightly adjust the irrigation schedule during the day. Kenyan farmers claimed that they would trust the tool to automatically calculate the correct amount of water most of the time, but they imagined instances this might not be the case. For example, if they had just installed the tool, they might want a few weeks to learn how it differs from their typical irrigation schedule. There could also be times that they would want to skip irrigation events, including if farmers wanted to harvest earlier than expected or if the system needed maintenance. For instances like these, participants said they would like to adjust the schedule as desired after a visual inspection at the end of an irrigation event. In the second iteration of this design concept, farmers were given the ability to add time to an irrigation event if they observed insufficient water delivery or to skip irrigation events entirely if desired. The order and duration of irrigation events were still automatically scheduled and communicated to farmers to enable manual valve operation.

3.5 Updated storyboard- and prototype-based interviews and focus groups to further evaluate the AS-MO tool and UX in EA and MENA

3.5.1 Design of a UX prototype that simulates user interactions

The design improvements found in Section 3.4.3 were incorporated into a physical prototype of the AS-MO tool and UX that simulated a farmer's daily interaction with it. Prototypes are known to increase the quality of feedback given by interview participants because they allow a potential user to imagine interacting with the proposed device [20, 68]. This mechanism was used to evaluate how farmers and stakeholders respond to the basic elements of the AS-MO UX, addressing the fourth research aim of this chapter. The prototype itself consisted of three components: a mobile phone, a control box, and a weather station (Figure 3-3).

GEAR Lab Irrigation Controller
Section 2: 45 minutes left

Open Section 3 and
confirm on your phone.

GEAR Lab Irrigation Controller - K...

Skip Section 1.

Irrigating Section 1 for 30 minutes. Next event is at 8:30am. 4:16 PM

Please close Section 1 and confirm. 4:16 PM

Section 1 is closed.

Add 10 minutes to Section 1.

You have added 10 minutes to Section 1. 4:17 PM

Please close Section 1 and confirm. 4:17 PM

Figure 3-3: The three components of the physical prototype used to facilitate interviews and focus groups. The phone (A) was equipped with a Telegram bot that stepped farmers through a key set of interactions with the tool. The control box (B) displayed the status of these interactions and directed farmers to interact on the phone. The low-cost weather station (C) showed farmers what data the tool might collect: wind speed, wind direction, ambient light, solar irradiance, precipitation, temperature, and humidity.

The phone was equipped with Telegram, a messaging app that uses data rather than SMS (Telegram FZ-LLC, 2023). Telegram users can have conversations with bots that deliver pre-programmed messages, and these bots can ask users short answer questions that determine the messaging path the bot takes next. For this study, a Telegram bot was created to walk participants through the following set of simulated AS-MO UX interactions:

- Provide farmers with a sample daily irrigation schedule, simulating the first message a farmer would receive each morning;

- Ask farmers if they approved of that day's irrigation schedule;
- Send a message prompting the farmer to manually open or close a valve when an irrigation event started or ended, respectively;
- Give farmers the ability to add an additional 10 minutes of irrigation time when an irrigation block is scheduled to end, and then update the schedule based on this choice; and
- Give farmers the ability to skip a block before irrigation starts, and then update the schedule based on this choice.

These new interactions aimed to bring farmers the scheduling flexibility that was shown as valuable in Section 3.4.3, allowing the research team to elicit feedback on this design modification.

The prototype control box consisted of an e-Ink screen mounted on a black box of a similar size and shape anticipated for the controller. Inside the box was a battery and a Raspberry Pi that carried out the Telegram bot's script. The box did not have any physical modes of interaction (e.g., buttons or dials), but it was designed to:

- Display the open/closed status of irrigation blocks based on confirmations a participant made in Telegram;
- Display a countdown telling the user when the next irrigation event was scheduled to occur; and
- Demonstrate to participants the anticipated size of a permanently-mounted control box (approximately 230x150x70 mm).

The prototype weather station included the number and type of weather sensors that would be required to generate an optimized irrigation schedule, including wind speed, wind direction, ambient light, solar irradiance, precipitation, temperature, and humidity. This allowed the research team to elicit feedback on the type of weather information that participants found most valuable.

3.5.2 Prototype-based interview methods

The physical prototype was designed to help participants describe what would be most valuable and most frustrating about the UX. To reach these aims, interviews and focus groups were conducted with potential users and market stakeholders in Kenya, Jordan, and Morocco, expanding regional coverage into two MENA countries.

During interviews and focus groups, an approach inspired by Lean Startup methodologies was followed [99]. Participants were first introduced to the updated tool design concept with a set of storyboards using the protocol described in Section 3.4.1. This set of storyboards reflected the two key design changes as described in Section 3.4.3.

After the storyboard introduction, participants were given the physical prototype designed to help them answer questions relating to the value and daily use of the proposed tool and UX. Specifically, (1) What is the most useful information they think the tool could provide? (2) How do farmers think they would or would not use the tool daily? and (3) What drawbacks do they think they would encounter with the tool's UX? Specific interview questions targeted these broader research questions, but the semi-structured nature of the interviews and focus groups meant that not all participants were asked the same specific questions.

During the study, it was made clear to participants that interacting with the prototype alone would not open or close valves, as the valves would not be automatic. Rather, the user would manually perform these actions in the field and then use Telegram on the phone to confirm once complete.

As the prototype was intended to assess user interactions rather than the water and energy savings one could realize with automatic schedule determination, a mock irrigation schedule was presented to the user. The durations of irrigation events were also shortened for the study, and participants were made aware of these adjustments.

Because the research goals sought to understand farmers' general satisfaction with the proposed UX, there were several less common interactions that the prototype did not simulate, including:

- Significantly changing an irrigation schedule (e.g., shortening or canceling irrigation events, or adding extra time to irrigation events before the event started);

- Inputting farm details into the tool (e.g., field layout, crop types, and growth stages of crops); and
- Providing farmers with forecasts greater than one day out.

In total, 22 prototype-based interviews and focus groups with farmers were conducted (seven in Kenya, five in Morocco, and 10 in Jordan), involving a total of 40 farmers (13 farmers in Kenya, 11 in Morocco, and 16 in Jordan). These farmers were associated with 22 farms, ranging from 3–10 acres in Kenya, 5–120 acres in Morocco, and 4–120 acres in Jordan. These farm size ranges in all three countries were representative of the ranges in each country for which solar-powered drip irrigation would be most feasible [115, 47]. Eight Kenyan farmers had previously participated in the initial set of interviews and focus groups, so they were already familiar with the design concept. Unfortunately, due to travel complications, three interviews in Morocco were conducted without the physical prototype. These protocols involved only the storyboards.

The prototype-based interviews were also conducted with 21 market stakeholders (seven in Kenya, four in Jordan, and 10 in Morocco) whose backgrounds are summarized in Table 3.3. Interviews with stakeholders followed a similar protocol as interviews with farmers and sought to assess the tool's potential as a viable product in EA and MENA markets. On larger farms, particularly in Jordan and Morocco, the anticipated price point range was increased from \$300–500 to \$700–1000. This change reflected that large farms often experience microclimates, so they may need several weather stations (on the order of three to five) to provide accurate forecasts. All interviews and focus groups took place in March 2022.

To analyze both farmer and stakeholder interviews, transcripts and notes were inductively coded [21]. Inductively coding allows for broad themes to be discerned from diverse datasets. The broad themes were sorted based on the frequency with which they arose in interviews. All protocols were approved by the Massachusetts Institute of Technology Institutional Review Board (protocol E-4098).

Table 3.3: Roles and affiliations of the 21 market stakeholders interviewed in the second portion of this study.

Role	**Affiliation**	**Affiliation description**	**Participant count**
Kenya-based stakeholders			
Irrigation engineer	Davis & Shirtliff	An irrigation equipment distribution company serving EA	2
Manager	Davis & Shirtliff	An irrigation equipment distribution company serving EA	2
Agronomist	Self-employed	Provides regular agriculture advice to farmers	1
Content creator	Shamba Shape Up	A media group that creates training videos for farmers	2
Jordan-based stakeholders			
Engineer/ manager	Hunter Industries	A developer & supplier of irrigation controllers	1
Engineer/ manager	Tadsheen	A company that helps farmers install solar & automation	1
Engineer/ policymaker	USAID Jordan	Jordan branch of the U.S. government's international development agency	1
Engineer	NDICO	Leading drip irrigation production & supply company in Jordan	1
Morocco-based stakeholders			
Agricultural reseracher	INRA	The National Institute for Agricultural Research (INRA) conducts agricultural research on Moroccan farms	3
Manager	ORMVA	The Regional Office of Agricultural Development (ORMVA) is a local government body	1
Manager	Heliotechnics	A supplier of solar & drip equipment, including controllers	2
Engineer	Quality Bean	An export company that supplies & supports farmers	1
Manager	Hortisud	An irrigation equipment supplier	1
Engineer	Hortisud	An irrigation equipment supplier	1
Manager	Agri4.0	An R&D company developing precision irrigation solutions	1

3.5.3 Results of the prototype-based assessment in Kenya, Jordan, and Morocco

Further substantiation of the tool's value

In 23 out of 36 interviews (nine in Kenya, seven in Morocco, and seven in Jordan), farmers asserted that the AS-MO tool would likely be adopted by farmers in the target user group, a result consistent with the preliminary study in Section 3.4.

The most valuable benefits of the tool according to participants were alleviating water scarcity concerns and preventing over-irrigation. Farmers and stakeholders alike noted that climate change has altered seasonal rains such that they are no longer predictable. Farmers can no longer reliably anticipate water availability based on historical trends. Participants claimed that an automatic scheduling tool could aid them as they plan irrigation events. As one Jordanian engineer explained, "We have not yet figured out the right software to connect farmers with their [irrigation] equipment, [but] if you provide a tool that will enable farmers to regulate the way they apply water the same way you regulate your car acceleration, you will get really impressive results."

Farmers in particular also noted that the tool could save them effort, money, and time, echoing the results of Section 3.4. Farmers in MENA who used grid-based systems frequently pointed out the high cost of electricity. They observed that by reducing the cost of solar panels, the tool could enable them to adopt solar, effectively reducing or eliminating their energy bill. Professionals in this region also pointed out that the tool could reduce system energy consumption and cost by encouraging farmers to reduce over-watering and over-pressurized system operation. This is why, as multiple stakeholders observed, a key aspect of the tool's value proposition is that it accounts for both water and energy use concurrently. Three stakeholders and two farmers were concerned that using the tool could potentially increase the amount of time that a laborer was needed on the farm. This discrepancy suggests the need to explore whether the tool saves or increases labor and time when used over long periods.

In 11 interviews, farm owners and stakeholders agreed that the suggested price points of \$300–500 and \$700–1000 for EA and MENA, respectively, were reasonable for the target users. However, the majority of participants did not think they could comment on the price because, as farm employees, they did not make purchasing decisions. No participants asserted that the proposed price point was too high, consistent with the results in Section 3.4. These results suggest that there may be promising markets of farmers in both EA and MENA that would value and adopt the proposed AS-MO tool at the proposed price points.

Farmer and stakeholder scheduling and operation UX preferences

Figure 3-4 summarizes the scheduling and operation preferences noted from the 36 farmer and stakeholder interviews and focus groups. Operation preferences are broken down by country.

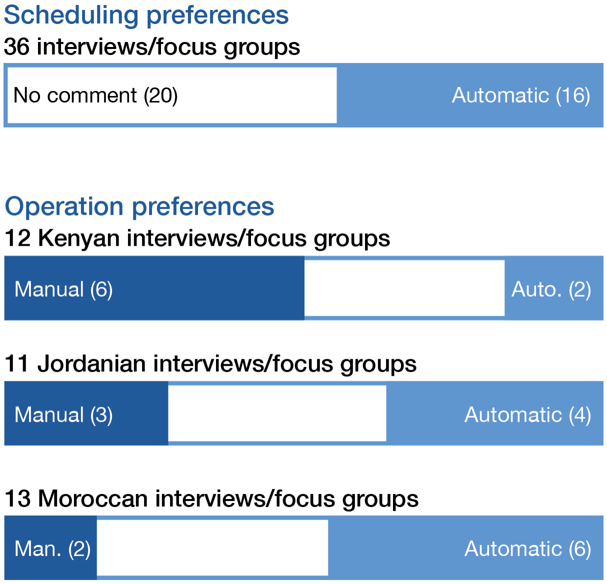


Figure 3-4: A summary of both farmer and stakeholder preferences for scheduling and operation. Automatic scheduling was preferred over manual scheduling by all participants who had a preference. Preference for manual operation over automatic operation differed by country. Not all participants mentioned a preference, so they are visualized by the white space.

In 13 of 22 farmer interviews or focus groups, participants noted that they particularly appreciated the automatic scheduling aspect of the AS-MO UX. This result, consistent with Section 3.4, suggests that this is an important feature for Jordanian and Moroccan farmers in addition to Kenyan farmers. Farmers noted that an automatically-determined schedule specific to their farm and weather conditions could improve their yields.

There was disagreement among farmers on their preference for manual versus automatic operation of valves. In 12 interviews or focus groups (two in Kenya, four in Jordan, and six in Morocco), farmer or stakeholder participants preferred automatic valve operation, while in 11 interviews (six in Kenya, three in Jordan, and two in Morocco), manual valve operation was preferred. The preference for automatic operation was particularly driven by MENA participants who operated or served on larger farms. On larger farms, participants claimed that automatic operation was worth the investment because laborers would otherwise need to walk long distances to manually operate valves, wasting time and potentially increasing labor costs. Several of the larger farms had already installed automated solenoid valves and asked if the tool could be adapted to operate those valves.

Kenyan farmers in particular favored manual valve operation over automatic operation, with only two of seven Kenyan farmers claiming a preference for automatic valves. Consistent with the preliminary results reported in Section 3.4, the manual valves were heavily preferred over solenoid valves due to their low cost. Study participants also noted that the reliability and familiarity with manual valves in the region could benefit Kenyan farmers more than solenoid valves. Several participants in Jordan also had a preference for manual valves, suggesting that an AS-MO UX could have promise in these markets.

The two design changes and updates to the AS-MO tool and UX described in Section 3.4.3 were well-received by participants in all three countries. The majority of farmers interviewed liked the ability to add more time or change the schedule slightly, suggesting that they value retaining some degree of manual control. Farmers also liked that the prototype used data rather than SMS. Both farmers and stakeholders mentioned that their local SMS rates were higher than local data rates. Participants commented that a data-based solution would be less expensive than an SMS-based one, increasing its chances of adoption.

Participants in all three countries commented on the importance of demonstrating the tool and UX to farmers before they would be likely to adopt the technology, a result consistent with literature about farmers in Tanzania, South Africa, and Morocco [75, 108, 12]. Nine farmers claimed they would need to closely monitor the tool on their own farm for a period of time before trusting that the automatic schedule determination was sufficient. Farmers and professionals alike expressed concern about the accuracy of the crop water demand estimation; engineers from Hunter Industries noted that the accuracy of this estimation would have to be within at least 10%, based on their experience designing irrigation controllers, to avoid negatively impacting crop yield. These results stress the importance of demonstrating the tool and UX before farmers can realize its full benefits.

Target specifications and desired features to consider when designing an AS-MO tool and UX

The results of the interviews can be consolidated into design features and target specifications for a precision irrigation tool that addresses the specific needs and constraints of farmers in EA and MENA. Table 3.4 shows how these design features and target values align with the functional requirements defined in Table 3.1. These results show how to design a high-performance, low-cost AS-MO tool and UX for resource-constrained markets.

Study participants suggested several features that they would like to see in future iterations of the AS-MO tool and UX design. Both farmers and stakeholders expressed a preference for using a custom app to communicate with the tool as opposed to using a messaging app like Telegram. Participants claimed that a custom app would provide more functionality, citing several key benefits.

First, participants noted that inputting the farm details needed for the automatic scheduling aspects of the tool could be easier with a custom app. Farmers and agronomists agreed that they would accept the need to update farm details when they change crops as long as it was easy. Several farmers reported changing their

Table 3.4: Key features and target values for a precision irrigation tool that meets the needs of small- and medium-scale farmers in resource-constrained markets.

No.	Requirement	Elements	Proposed Feature or Target Value
1	Improve system efficiency	Increase water use efficiency Increase energy efficiency (solar)	10-50% water savings, comparable to sensor-based methods [110] 10% increase in energy efficiency (profile matching) [130] 20% power system cost reduction [115]
2	Case-specific	Scalable calibration procedure Easy-to-use data entry interface	Input crop type, soil composition, field layout, GPS Characterize hydraulic system operation on-site
3	Create irrigation schedule and communicate with user	Intuitive user interface Non-disruptive communication frequency Compatible with local operating system	Keep user in the control loop with AS-MO Update irrigation schedule daily Allow user to adjust or skip events App-based interface, using data (not SMS) iOS and Andriod compatible
4	Accurate irrigation amount	Accurate soil moisture estimation Accurate weather data/forecast	±10% water demand accuracy, according to interviewed stakeholders Daily, site-specific weather forecast Real-time weather and hydraulic measurements
5	Reliable operation	Reliable on-site connectivity Robust energy management/storage Robust calibration Simple maintenance Weatherproof	WiFi or local network (e.g., LoRa) Power always available for scheduled irrigation Calibrated values accurate throughout cycle/season Locally-available or standard hardware IP68 enclosure (weatherproof)
6	Affordable	Low-cost (compared to existing tools) Minimal specialized hardware	\$300-500 (Kenya) \$500-700 (MENA) Locally-available or standard hardware Cloud-based computation

crop selections every few weeks, while others remained more consistent. Participants noted that the process of entering and updating farm details could be cumbersome if designed poorly. This suggests that particular consideration should be put into this interface for the tool to be widely adopted. A custom app would allow for the greatest flexibility when inputting these key details.

Second, a custom app would allow different users to visualize their farm data in different ways, reflecting differences in the types of information that various stakeholders reported finding the most valuable. Farm managers and farm employees reported that detailed data on crop irrigation needs and weather forecasts would be most valuable. Conversely, farm owners reported that they would be less concerned with their farm's daily operational status and more concerned with the overall status such as whether the system was working well and the crops were healthy. Distributors noted that they could use system operating data to monitor the equipment that they had sold that might still be under warranty. These results demonstrate that a variety of interfaces highlighting different information might be needed to account for the diversity of user roles. A custom app could provide this level of flexibility.

Finally, several participants were concerned that a messaging-based interaction could be difficult for illiterate laborers to use. An app would allow for the use of more symbols, or even voiced instructions, making the tool more accessible. Several participants noted that for literate farmers, the ability to use the app in their local language would be important as well.

While a custom app was strongly suggested by a majority of study participants, it was also noted that a custom app could not be used by farmers who have feature phones. Only one study participant used a feature phone with all other participants owning smartphones. However, this study targeted early adopters who might be more technologically savvy than the larger market, suggesting that further market analysis should be done to understand this need. Studies have projected that by 2025, 84% and 61% of all cellular connections in MENA and Sub-Saharan Africa, respectively, will be smartphone connections [50, 51].

In addition to a custom app, several other features were mentioned by study participants as being potentially useful. While most farmers preferred for the main interaction to be through their phones, 11 participants suggested that farmers should have the ability to interact with the control box without a phone. Numerous reasons were cited as to why a phone might not be available. For example, the phone could be broken, the battery could be dead, someone else could be using the phone, or the cellular service could be poor. Seven participants in Jordan and Morocco claimed that a well-designed app would be sufficient and that they would not need any interaction with the control box. However, these participants had larger farms with potentially more access to capital and did not report having the phone and service problems reported more frequently on smaller farms. These results suggest that critical interactions with the AS-MO UX should be integrated into a control box design, so that farmers who need it have consistent access. Further, local wireless network options, such as LoRa, should be considered to ensure good on-site connectivity.

There was disagreement among participants about how farmers would use the tool on farms with multiple irrigation laborers. Seven farmers reported that they would want the tool to notify multiple phones with irrigation instructions. Five farm managers said they would want to receive the notifications first themselves and then send a message or call to the appropriate laborer to relay the instructions. These results suggest that having the option to connect multiple phones may be beneficial to farmers who choose to use it.

Tool functionality within larger agricultural ecosystems

Multiple study participants proposed ideas on how the AS-MO tool could work within larger agricultural systems, like water supply networks, farmer-training networks, data-sharing networks, or fertigation systems. Several government officials claimed data from this tool could provide a better understanding of how much water is being used in the region, enabling improved management of water supply networks. Regarding farmer-training networks, seven participants, both stakeholders and farmers, were concerned that farmers would need specific training before using this tool. Training can be difficult to conduct in remote farm areas, and this is already a large barrier to the adoption of irrigation equipment and agricultural practices in the EA and MENA [72, 100, 67]. Participants reported that the need for training on this tool should be minimized in order to increase adoption rates. Further work on developing an easy-to-use interface could alleviate this concern.

Several farmers suggested alternative ways to use the weather information that the tool provides. Multiple farmers were interested in using the tool's weather forecasts to plan non-irrigation farm events, such as knowing when to protect crops from potential frosts or scheduling planting and harvesting. Weather forecasts, if predicted up to seven days out, could advise them on when to hire additional labor for these events. One farmer suggested that he could disseminate the weather information to his neighbors because there was no current reliable source of weather data in his area. These alternative ways to use weather predictions could be further incorporated into the tool's design, increasing its functionality. Longer-term weather forecast software may need to be developed or added to the tool to accomplish this.

Several farmers wondered if the tool and UX could provide guidance for farm tasks beyond just irrigation scheduling. Six participants, particularly those who operate or serve larger farms, said it would be helpful if the tool also included fertilizer scheduling and operation. Five participants claimed it would be helpful if the tool could send alerts if something were wrong with the irrigation system. The examples they gave included clogged filters, clogged drip emitters, and burst pipes. These results suggest that expanding the tool's capability to aid with farming tasks beyond irrigation scheduling could increase its value to farmers.

3.6 Discussion

This work demonstrated that the proposed AS-MO tool and UX has the potential to bring the efficiency benefits of precision irrigation to medium-scale farms in Kenya and small- and medium-scale farms in Jordan and Morocco. It could do this by bridging the gap between existing, expensive precision irrigation technologies and affordable, easy-to-adopt irrigation methods.

Data from the study validated the assumptions made in Section 3.1 about the potential benefits of an AS-MO irrigation control method over the other methods in Figure 3-1. First, compared to both manual scheduling methods (top half of Figure 3-1), an AS-MO UX was hypothesized to address problems that are hard for humans to solve alone, such as creating efficient, reliable irrigation schedules. Discussions with farmers confirmed that doing so was difficult, time-consuming, and sometimes not possible without the use of sensors and calculations. The increase in efficiency and reliability provided by automatic scheduling was found valuable by most farmers, confirming initial hypotheses.

Second, compared to automatic control and automatic operation (lower right of Figure 3-1), an AS-MO tool architecture was predicted to deliver value to farmers for its familiarity and affordability. Some farmers preferred manual valves over automatic ones because they were concerned about the reliability of solenoid valves, a technology with which they had little familiarity. Several farmers also valued the ability to continue visually inspecting each block after each irrigation event. Farmers' preferences to continue certain practices that are currently a part of many farms' operations suggest equipment familiarity is a priority. Farmers, particularly farm owners, also expressed interest in the AS-MO tool because it was lower cost than a fully-automated system. These results suggest that the affordability of a new tool is also a priority for the targeted farms, as predicted.

Results from Kenya, Jordan, and Morocco are anticipated to be applicable to the larger regions of EA and MENA so differences in farmer preferences between the three countries could also predict differences in the two regions. One key difference between the regions was that it appeared that several interviewed Jordanian and Moroccan farmers were more familiar with current precision irrigation techniques than farmers in Kenya were. They were more excited about a fully automated system because they knew and trusted automated valves. On the other hand, Kenyan farmers and stakeholders more frequently expressed skepticism about automated valves, claiming they might break frequently.

A second difference between the regions was that there were mixed preferences for manual valve operation over automatic in Jordan and Morocco compared to a strong preference for manual operation in Kenya. While these results showed a slight preference for full automation in the Jordanian and Moroccan markets, it does not necessarily mean that an AS-MO tool could not provide value in the MENA region. Wider ranges of farm sizes were interviewed in Jordan and Morocco than in Kenya, and the larger farms were particularly interested in automatic valves. These large farms appeared to have more access to capital than the other studied farms, suggesting that the AS-MO tool concept might not be applicable to farms that fit this profile. However, there was strong interest in manual valves among the smaller farms in Jordan and Morocco which appeared to have less access to capital, suggesting there is likely a MENA market sector that is interested in an AS-MO tool in the way the Kenyan farmers were. Future exploration of the EA and MENA markets could confirm if the differences seen in Kenya, Jordan, and Morocco reflect the differences between EA and MENA as whole regions.

This study revealed insights about which features farmers prioritize when interacting with an AS-MO UX, notably flexibility and low operating costs. Design updates to the proposed UX allowed farmers to slightly adjust the auto-generated schedule throughout the day. This feature was valued by participants in all countries, suggesting that farmers who do not already use automation may not be comfortable with full automation. If this is the case, it is important to put the final control in farmers' hands and give them the flexibility to take as much or as little automated advice as they like. Therefore, the AS-MO approach may be a way to successfully introduce farmers to automation who might not trust it at first. A second design update that was appreciated by study participants was the choice to use data-based messages over SMS to communicate with users. The original AS-MO design concept was developed with low capital costs in mind. However, the strong preference for low-cost data-based messages demonstrates that users are sensitive to operational costs as well. Future design decisions should keep this user need in mind to address any other ways low operating costs could be realized. The functional requirements and design features and targets identified in this study outline a process for creating this technology. The strategy of pairing automated scheduling with manual actions could open new areas for innovation in precision agriculture while serving a broader range of users' needs.

The proposed AS-MO tool and UX could potentially be a good segue product for farmers who are transitioning from fully manual to fully automated. Several study participants pointed out that it would be beneficial for the tool to be adapted to include automatic valve operation, especially on larger or wealthier farms. This result suggests the participants saw the potential for the AS-MO tool to be "upgraded" from a semi-manual/semi-automatic tool to a fully automatic tool according to users' needs. There are likely cases where a farm first sees a need to address the challenge of automating irrigation schedules, so they adopt the AS-MO tool. Once that farm grows to the point where manual valve operation also becomes challenging, the farm could install solenoid valves and a new control box to operate them. At this point, the farm could continue using the same automatic scheduling methods as the AS-MO tool used, so the irrigation schedules are familiar and trusted. In the app, the farmer could input that the farm is now fully automated, and the tool could start controlling the solenoid valves rather than sending instructions to laborers' cell phones. If this tool could ease the transition from fully manual to fully automatic, it could help farmers adopt further benefits of conventional precision irrigation, like automatic operation.

This work demonstrates the successful use of a methodology in which the research team identified opportunities to automate complex tasks while designing ways for users to complete these tasks in simpler, manual ways. The goal of this approach was to gain some benefits of automation while also realizing other benefits of manual work in order to lower overall product costs. Interviewees suggested this semi-automatic/semi-manual product architecture could be valuable if applied to fertigation, suggesting that this approach could have implications past the specific example of irrigation in the MENA and EA markets. Additional opportunities could include home gardening or landscaping. To apply a semi-automatic/semi-manual architecture to a new area, it is helpful for researchers and designers to break down a problem into the necessary actions (e.g., scheduling and operation, in this case). They can then understand which actions are simpler to perform manually and which would be more difficult. For the difficult actions only, researchers and designers would then identify ways in which technology could improve those actions. New technology may need to be invented to communicate complex operations to users who are carrying out manual actions. This strategy is particularly appropriate for resource-constrained contexts. In these settings, the value of a product can be increased by selectively introducing automation while costs are minimized by continuing manual labor otherwise.

The methods used in this work provide an example of how to assess a new technology design concept and its potential adoption before launching it as a product. Consistent with the literature, the visual storyboards proved useful in communicating novel concepts to potential users who had different cultural and language backgrounds than the research and design team. The prototypes allowed interviewees to simulate using key aspects of the product. Because interviewees could imagine the UX, they could provide feedback before a full product was designed and built. This two-part design process could be adopted by other designers and researchers working in cross-cultural contexts to provide them with similar useful feedback.

Several limitations existed in this study. The small number of farmer interviews does not necessarily give a generalized opinion of all potential users in EA and MENA. To attempt to mitigate this limitation, lead users, early adopters, and market stakeholders were recruited for the study. However, because these participants were more familiar with advanced technology, they might have a higher preference for automation than the general population would. This may have led to more disinterest in the AS-MO tool than is potentially accurate in a group of target users.

A second limitation is that users did not interact with a fully-functioning prototype for an extended period of time. The prototype performed basic interactions, not in-frequent or edge-case interactions like inputting details of a farm or managing a failure in the system. These interactions might be tedious or particularly valuable to farmers, but without simulating them, it remains unknown. The prototype also did not calculate an irrigation schedule specific to a farm but instead used a preprogrammed schedule. This means farmers could not see the automatic determination of irrigation schedules working in action. Had farmers seen a higher fidelity prototype, they might have had a stronger critique of the automatic scheduling aspect of the UX, especially if it calculated a schedule drastically different from what they expected.

Both EA and MENA farmers claimed it was important to see demonstrations so they could evaluate their trust in a device. All of these scenarios mean interviewees had limited amounts of information on which to evaluate the AS-MO tool and UX. The research team believes the information was sufficient given the design stage of the concept, but further testing should include the long-term use of a working prototype with recurring user feedback as the concept develops.

3.7 Conclusions

The objective of this chapter was to propose and evaluate a potential means of bringing the water and energy efficiency benefits of precision irrigation to resource-constrained regions like EA and MENA. To do this, a design concept for an AS-MO tool and UX that could communicate complex, but resource-efficient irrigation schedules to farmers was characterized. To evaluate this concept, a two-part development process was implemented. First, storyboards of the design concept were shown to Kenyan farmers and market stakeholders to elicit feedback that was used to update the design concept. Second, a physical prototype of the tool's UX and updated storyboards were used in Kenya, Jordan, and Morocco to facilitate further interviews and focus groups with farmers and stakeholders.

The results demonstrated that the proposed AS-MO tool has the potential to enable target farmers to realize the energy- and water-saving benefits of precision irrigation with reduced, lower-cost infrastructure. The majority of all interviewed farmers were interested in the automatic scheduling aspect of the AS-MO tool. They recognized how implementing water- and energy-efficient schedules could save them time, effort, and money on their farms. Kenyan farmers and small-scale farmers in Jordan and Morocco also liked the manual valve operation that an AS-MO UX affords. They felt more confident in adopting low-cost, familiar hardware like manual valves over solenoid valves. These results indicate a potential market for precision irrigation technology designed specifically for resource-constrained farmers.

Interviews with farmers and stakeholders also provided insights on how farmers might best interact with the AS-MO UX. Results suggested that a smartphone app should be designed in order to enable key user interactions with the tool. A data-based solution, like an app, would be less expensive than an SMS-based solution, meeting the user need for low operational costs. Results showed that it was valuable to give farmers the flexibility to change the predetermined schedule, even slightly. Farmers liked the ability to add time to each irrigation event in case they thought the tool delivered an insufficient amount. They also liked they could shorten, pause, or cancel an event if needed. An app-based interaction should include different data visualizations for various user profiles, such as managers, owners, and laborers. Further, a limited set of critical interactions should be made possible on the permanently-mounted control box for when phones are unavailable. A screen that shows the status and several buttons or a dial could meet this user need.

Stakeholders and farm owners in a position to buy such a tool suggested the tool has the potential to become a viable commercial product in the studied countries. Several stakeholders claimed it could benefit the growing number of solar-powered drip irrigation users. All participants who commented on the estimated price point of the tool suggested it would be affordable to target users.

To bring the AS-MO tool concept to fruition, further research is needed to learn how farmers interact with a functioning AS-MO tool for an extended period of time. This study only addressed the core interactions of the proposed AS-MO UX. Other interactions—like allowing farmers or agronomists to input farm details—need to be prototyped and tested. It is also necessary to study the AS-MO UX over the course of a season to understand how to improve it for future users. Farmers in both regions claimed they would need to see the AS-MO tool installed and functioning on a farm to fully evaluate its potential benefit to them. This tool must be demonstrated under these conditions to gain further user feedback. The study also assumed that the perspectives of Kenyan farmers and Jordanian and Moroccan farmers would represent the perspectives of EA and MENA farmers, respectively. Future work should expand regional coverage to confirm or deny this assumption. If denied, learnings from other countries should be integrated into the tool to increase the likelihood of its adoption throughout the regions. With these next steps, future development on an AS-MO tool and UX could help bring water- and energy-efficient irrigation to resource-constrained regions like EA and MENA.

Chapter 4

Water Savings and User-Centered Validation of an Automatic Scheduling-Manual Operation (AS-MO) Irrigation Tool

4.1 Introduction

The objective of this chapter is to demonstrate that long-term use of an automatic scheduling-manual operation (AS-MO) irrigation tool increases water savings, compared to fully manual irrigation, a common practice on resource-constrained farms. Through two case studies—one in Jordan and one in Kenya—this work seeks to show that farmers use this tool as intended.

The United Nations' second Sustainable Development Goal (SDG 2) aims to achieve food security, improve access to nutritious food, and promote sustainable agriculture by 2030 [112]. It is particularly crucial to address this goal in low- and middle-income regions like East Africa (EA) and the Middle East and North Africa (MENA). With growing populations in these regions and high levels of undernourishment, food security can only be realized with increased food production [126, 36].

Previous work has shown that medium-scale (2–6 hectares) farms in EA and small- to medium-scale (2–10 hectares) farms in MENA are a growing group of farms that have the potential to feed the expanding populations in their respective regions [59, 115, 47]. Serving the needs of farmers on these farms can help them increase crop cultivation and meet demands.

Introducing irrigation on farms is a successful way to increase food production [10, 95, 83]. Further, irrigation—as opposed to rainfed agriculture—helps farmers cultivate more nutritious crops, like fruits and vegetables [16]. While increasing the adoption of irrigation aligns with SDG 2's aims of food security and improved nutrition, it has the potential to conflict with its further aim of sustainable agriculture. Irrigation is a water-intensive process that uses 70% of the world's freshwater withdrawals each year [34]. When regions rapidly increase irrigation without doing so sustainably, severe negative consequences can follow. For example, the recent agricultural revolutions in China and India have depleted many of the countries' freshwater resources, leaving farmers to face extreme water stress [120, 58]. To increase food production while avoiding negative impacts on freshwater sources, farmers must adopt water-efficient technologies and practices.

Drip irrigation—the practice of delivering water directly to crops through a network of pipes and emitters—is an irrigation method that uses up to 50% less water than conventional irrigation methods like flood irrigation [9]. However, for drip systems to achieve this water-saving benefit, correct operation of the equipment and control over the system is crucial. If too much water is delivered, water use efficiency—the ratio of crop produced to water used—decreases. If too little water is delivered, crops can become stressed and yields can decrease. Further, correct operation and control enables systems to deliver the ideal amount of water for specific farms' growing conditions, like weather, soil type, and crop varieties. In practice, achieving this optimal balance is difficult.

Precision irrigation solutions have emerged to address the challenge of optimizing irrigation water use. By collecting detailed farm data, employing advanced algorithms, and interfacing with solenoid valves throughout the hydraulic network, precision irrigation solutions are capable of calculating and implementing optimal irrigation schedules [2, 103, 40]. These solutions primarily focus on increasing water use efficiency or address the difficulty of using variable power sources such as solar panels [2, 25, 18]. Various strategies are employed to achieve this goal, including real-time adjustments based on retroactive agronomy measurements, utilization of predictive modeling for real-time irrigation adjustments, optimization of irrigation schedules to minimize water consumption, and aligning irrigation power requirements with the available solar power profile [1, 23, 71, 130, 74].

Unfortunately, many precision irrigation tools rely on arrays of expensive sensors and at least one solenoid valve per irrigation block throughout the field. This equipment can cost up to tens of thousands of dollars, making it inaccessible to the resource-constrained, small- and medium-scale farmers addressed in this work [116]. Precision irrigation equipment is also often complex, requiring advanced training for proper use. This barrier hinders the millions of farmers who do not have access to high-quality extension services [108, 78, 69].

The work conducted in Chapter 3 of this thesis suggested that a tool with an AS-MO architecture could help medium-scale, resource-constrained farmers realize the water-saving benefits of precision scheduling to farmers at affordable rates. Chapter 3 proposed an AS-MO tool that could take advantage of the automatic scheduling benefits of precision irrigation algorithms while integrating the familiar, inexpensive hardware of manually-operated valves. The tool and its associated user experience (UX) were evaluated in a two-stage design process that solicited feedback from potential users and key market stakeholders in Kenya, Jordan, and Morocco. These interview participants provided feedback on how to improve the tool and UX, and an updated design is shown in Figure 4-1. The top left of Figure 4-1 shows how the proposed tool coordinates irrigation events using the Predictive Optimal Water and Energy Irrigation (POWEIr) controller theory, a theory that was co-developed with the work described in Chapter 3 [97]. The POWEIr theory first forecasts available power (represented by the dark blue line) and predicts the pumping energy an irrigation system needs to meet crop water demand (light blue boxes). It then schedules these event blocks given the anticipated available power.

Aligning with the user needs of resource-constrained farmers, the POWEIr theory does not rely on soil moisture sensors but instead uses soil water balance calculations [9] and several inputs from the farm to compute soil moisture estimations in the cloud (left-hand side of Figure 4-1). The necessary farm inputs include readings from an inexpensive weather station, solar panel power readings, and user inputs regarding system component specifications and agronomy details (e.g., solar array capacity, pump operating points, irrigation block areas, crop types, and soil texture).

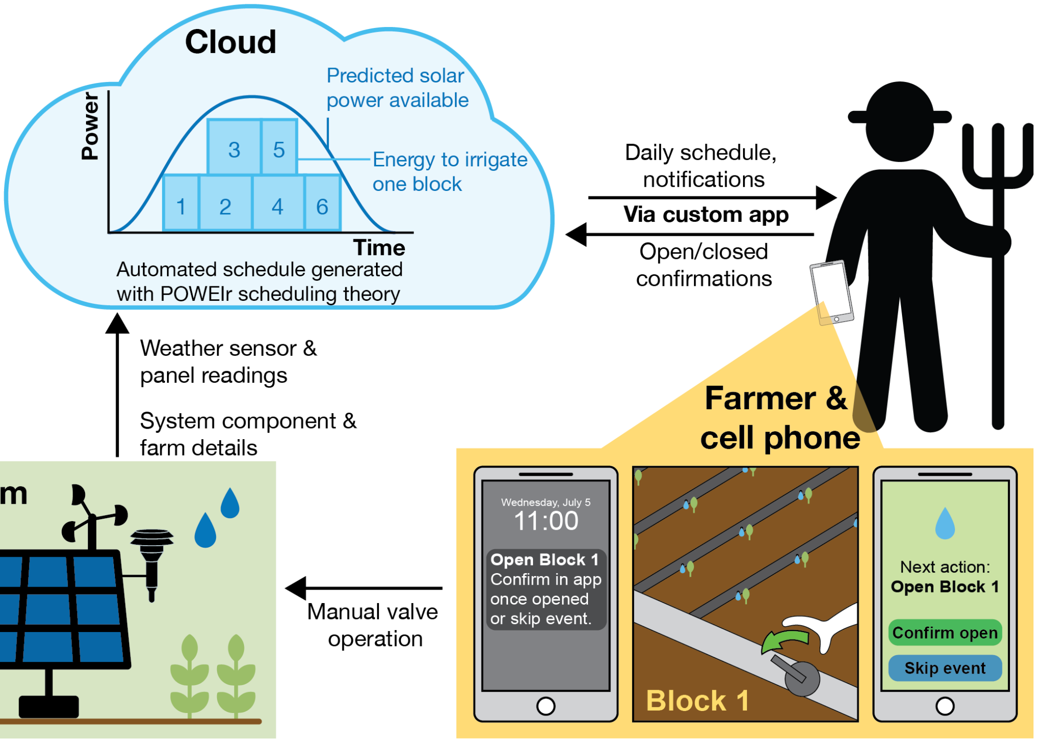


Figure 4-1: Overview of the updated AS-MO tool and user experience that reflects the key design changes found in Chapter 3. On the left, details about the farm and irrigation system are fed into the Predictive Optimal Water and Energy Irrigation (POWEIr) scheduling theory, a theory that automatically generates efficient irrigation schedules. On the right, this schedule is communicated to farmers for manual operation via notifications from a custom app. These notifications are sent at the beginning of the day and at the start and end of each irrigation event. These messages remind farmers of the actions needed to carry out the generated schedule. The custom app also provides farmers the flexibility to skip irrigation events before they begin or to add time to the end of irrigation events. When farmers confirm actions or choices in the app, they inform the algorithm how closely the schedule was followed so the next day's schedule can generate accordingly.

The right-hand side of Figure 4-1 shows how the AS-MO tool's UX communicates an irrigation schedule to users via a custom phone app. At the beginning of each day, the POWEIr theory computes a schedule and sends this information to the farmer's phone. A push notification lets the farmer know when this schedule has been produced. Within the app, the farmer can accept or slightly modify this preliminary schedule. Once the accepted schedule begins, the farmer's phone receives additional notifications at the start and end of each irrigation event (lower right of Figure 4-1). These notifications are intended to remind farmers to manually open or close valves. The work in Chapter 3 found that it was important to give farmers a degree of scheduling flexibility. To provide this, when an opening or a closing notification is sent, the app gives farmers the option to skip an irrigation event before it begins or add additional time to the end of an event, respectively. Depending on their choice, the farmer would then manually open or close valves as advised or chose the alternate option. They would then confirm their action or choice in the app. Because farmers might not perform an action on time, this confirmation allows the POWEIr theory to measure how long each irrigation event was in practice without relying on sensors throughout the field. The flexible POWEIr theory can accommodate these changes to irrigation schedules, but it must know the accurate durations of past irrigation events to calculate optimal future events. The interaction process described above is repeated throughout the day for each irrigation event.

The work conducted in Chapter 3 showed how this proposed AS-MO tool could allow for the adoption of water-efficient irrigation practices without the need to install expensive automatic valves or many sensors throughout a field. This could enable farmers to realize the water-saving benefits of precision irrigation while installing minimal additional hardware. However, the AS-MO tool and UX assessed in Chapter 3 were not validated through long-term testing, so farmers' reactions to this type of UX remain unknown. For example, farmers could potentially ignore notifications, or they could become frustrated with frequent reminders. In these cases, the tool might be disadopted, and the water-saving benefits would not translate. To learn how farmers use and perceive the proposed AS-MO tool and its associated UX, a prototype of the tool was demonstrated over an extended period on one farm in Jordan and one in Kenya.

The specific objectives addressed in this chapter are to:

1. Validate that, compared to conventional irrigation practices, medium-scale farmers use an AS-MO tool in a way that saves water while still providing adequate irrigation, by measuring water use on two farms;

2. Demonstrate that the AS-MO user experience is successful and operates as intended, via user observations and interviews; and

3. Determine the features of an AS-MO tool that farmers find most valuable and establish what added or changed features could increase adoptability of an AS-MO tool, by synthesizing results from the field trials, user observations, and interviews.

By demonstrating the long-term use of an AS-MO tool in real farm conditions, we show how it can be designed to fulfill farmers' irrigation needs. With those needs met, farmers could be more likely to adopt this tool and the water-efficient irrigation practices it enables. When adopted at scale, this tool could help address the global water scarcity challenges we face with a growing global population.

4.2 Design of an AS-MO tool prototype

To achieve the aims addressed in this Chapter, two functioning AS-MO tool prototypes were designed and built to be tested on farms. This section details how the automatic scheduling and the manual operation were accomplished with the POWEIr scheduling theory, physical hardware, and a custom phone app that could deliver realistic AS-MO UX to study participants.

4.2.1 Automatic scheduling achieved through POWEIr theory and physical hardware

To facilitate automatic scheduling, the prototype used the POWEIr theory introduced in Section 4.1 to build water-efficient irrigation schedules each day. This theory is currently being validated on a farm in Morocco. In that experiment, automatic solenoid valves are used to carry out the POWEIr-generated schedule. The water usage on the experimental farm is compared to the usage on a farm that employs conventional, fully manual irrigation practices. Preliminary results from this case study demonstrated that the POWEIr theory used 44% less water compared to conventional irrigation while delivering just a 9% decrease in crop yield. The AS-MO prototype evaluated in this thesis uses the same underlying theory to generate daily irrigation schedules but replaces the solenoid valves with manual valves and human operators to understand if similar savings can be realized.

The POWEIr theory relies on several weather readings. To gather these inputs, a weather station was one component of the AS-MO prototype. Mounted in a central farm location, the weather station monitored wind speed, wind direction, ambient light, solar irradiance, precipitation, temperature, and humidity (WS-1551-IP by Ambient Weather, Arizona).

A second prototype component, a custom-designed control box, received the weather data and sent it to the cloud. An embedded compute system (Cerbo GX by Victron Energy, The Netherlands) recorded, buffered, and transmitted data via an LTE router (RBSXTR&R11e-LTE by MikroTik, Latvia). The control box was powered by batteries that were charged via solar panels and regulated by a solar charge controller (SmartSolar MPPT by Victron Energy, The Netherlands). The control box also acted as a data acquisition unit for collecting experimental data. The types of data collected are described further in Section 4.3.

The control boxes for the two prototypes varied because different configurations of the POWEIr theory were implemented on the two experimental sites. In the configuration deployed in Jordan, the prototype controlled the pump operating point and managed battery-based energy storage. However, in Kenya, the prototype control box did not interact with the pump or power system. Despite these differences, both prototypes collected weather data and provided scheduling recommendations to farmers in a similar manner. Consequently, these discrepancies were not anticipated to affect the objectives addressed in this study.

4.2.2 Manual operation achieved through a custom phone app

To facilitate manual operation, a functional app was developed to communicate the automatic schedule to farmers for manual operation. The app, intended to be installed on study participants' cell phones, was designed to serve the important role of closing the loop between scheduled irrigation events and the actions farmers take on the field. This feedback is critical because the POWEIr theory schedules future irrigation events based on past water delivery. Because of this, the POWEIr theory is well-suited for an AS-MO tool because it can account for past user errors (e.g., delaying actions or skipping irrigation events) when it schedules future events.

The app's design was informed by the work in Chapter 3 that assessed the AS-MO UX with potential users and market stakeholders. The app consisted of five key pages (Figure 4-2): the irrigation schedule page, the action confirmation page, the weather page, the block overview page, and the block details page.

First, one page displayed the POWEIr-generated daily irrigation schedule (Figure 4-2a). The current date was displayed at the top of this page, so users could confirm the schedule was up-to-date. A horizontal bar representing the current time moved down the schedule as the day progressed. Scheduled irrigation events populated the schedule. The event color corresponds to the irrigation status—a function of the time of the scheduled irrigation event relative to the current time (current, past, or future) and what the user confirmed the valve state to be (open or closed). Color mappings are provided in Table 4.1.

In order to minimize sensors on the field, the AS-MO tool did not know the irrigation status of the farm. It relied on users to accurately update valves' open or closed state in the app. They did this through the action confirmation page (Figure 4-

Okra1

04:10 PM to 04:40 PM

irrigation 4000 L in 30 minutes

PLEASE OPEN

Grape6

Soil moisture is GOOD

CROP DETAILS
CABBAGE
15 weeks
Planted 19/02/23
1 crops per bed

LAYOUT DETAILS
0.08 acre
16 m block width
20 m block length
16 beds

DRIP DETAILS
1.0 L/hr emitter
1.0 L/hr emitter spacing
1.0 bar activation
PC emitters

Figure 4-2: Key screenshots of the AS-MO app: (a) the daily irrigation schedule generated by the POWEIr theory, (b) the action confirmation page asked users to confirm valve-opening or valve-closing action, (c) the weather page displayed a three-day forecast, (d) a list of irrigation blocks provided an overview of all blocks, and (e) a detailed page of irrigation blocks allowed users to edit block parameters.

Table 4.1: Event color and action confirmation window text for possible irrigation statuses.

Relative time of irrigation event	**User-input valve state**	**Event color**	**Confirmation window text**
Current	Open	Blue	"Close early"
Current	Closed	Red	"Please open"
Past	Open	Red	"Please close"
Past	Closed	Gray	"Open again"
Future	Open	Red	"Please close"
Future	Closed	Gray	"Open early"

2b), which appeared if a user clicked an event on the schedule page. The confirmation window text (provided in Table 4.1) depended on the event's irrigation status. At this design stage, the app was not designed to give users specific choices to skip irrigation events or add additional time to irrigation blocks. However, study participants were informed that they had these options and could postpone any direction, simulating the flexibility an AS-MO tool could afford.

A third page showed users a three-day weather forecast that included temperature, cloud cover, wind speed, and solar irradiance (Figure 4-2c). Farmers interviewed in Chapter 3 stressed the importance of knowing weather forecasts. They claimed this information could help them make both irrigation and non-irrigation decisions on the farm. Including the forecast in the AS-MO app was a design choice aimed at delivering this valuable information to users.

A fourth page showed an overview of the irrigation blocks, providing information about crop type, area, and growth stage of each block (Figure 4-2d). At the bottom of this page, there was an option to add new blocks. If a user clicked a block icon, they reached a page showing specific details of that block (Figure 4-2e): crop type, planting date, block width, block length, number of beds per block, number of crops per bed, and specifications of the drip emitters used in that block (e.g., flow rate, spacing, activation pressure, and pressure-compensating capability). The soil moisture level, estimated with the POWEIr theory, was also displayed on a scale. The scale was designed to be easy for farmers to interpret. The scale had red areas to convey the soil moisture was too high or too low. The green range signaled the soil moisture was acceptable. On the block detail pages, users could edit the parameters of existing blocks. These parameters were key inputs to the POWEIr theory, so it was important that users could enter them accurately. Prior work suggested that inputting or editing these details might be cumbersome to farmers, so the design of these pages attempted to minimize user error and frustration.

Additional pages, not shown in Figure 4-2, were a login page and an account settings page where farmers could update their well depth and soil type (important inputs to the POWEIr theory), change the app's display language, or logout.

Throughout all pages, the app was designed with minimal text to enable use by farmers without high literacy skills. This was accomplished by using colors, numbers, icons, and pictures when possible.

To test the key aspects of an AS-MO UX, the app's design enabled four key farmer interactions with the AS-MO tool. Specifically:

- The app sent the type and frequency of notifications expected from the AS-MO tool, allowing the research team to elicit feedback on the type of directions study participants found helpful. The app sent three types of notifications:
  - Early each morning, a push notification was sent to inform users when the first irrigation event was scheduled to begin or if there were no scheduled events that day.
  - Throughout the day, further push notifications were sent at the start and end of each scheduled event, advising users to open or close manual valves, respectively. The notification text included the directed action ("Open" or "Close") and the specific irrigation block to which the action applied (e.g., "Grapes Block 5").

  - Finally, reminder notifications were sent if users ignored any previous notifications. These reminders were pushed every five minutes until the user confirmed an action or until the scheduled event ended.

- The app enabled the key scheduling flexibility expected in the tool, a feature that was found important during interviews in Chapter 3. Study participants could ignore any notification but get a reminder five minutes later. This meant that if a user wanted to add ten minutes to the end of an irrigation event, they could wait for the second reminder. If they wanted to skip an irrigation event entirely, for example, users could ignore notifications for the duration of the event.

- The app enabled users to enter and edit key parameters that were necessary inputs into the POWEIr theory. This capability was possible through the block overview and block detail pages.

- The app provided users with key information about a farm's status, allowing the research team to gather feedback on the most useful details for farmers and identify any missing information. In addition to the daily irrigation schedule and the open or closed state of the valves, the app displayed the three-day weather forecast, estimated soil moisture levels for each block, and block parameters.

These interactions were considered the most critical to test an AS-MO UX at this design stage. The experimental methods discussed further in Section 4.3 describe how these interactions were assessed with study participants.

The app was designed by the research team in Figma (by Figma, California), and the front end was built by contractors for use on Android. The research team developed and deployed the backend system that generated the irrigation events, numerical values, and notifications used to populate the app pages. Communication between the app and the backend system was done via MQTT and Firebase Cloud Messaging (by Alphabet, California). All data from the app and backend systems were stored in an InfluxDB (by influxdata, California) database on the research team's servers. If the app was offline, a red caution sign was displayed at the top of all app pages to alert users.

4.3 Methods for assessing water savings and adoption potential of an AS-MO tool

To understand how the proposed AS-MO tool performs on real farms, two prototypes were used for extended periods of time by farmers on two farms: one near Irbid, Jordan, and one near Rurii, Kenya. These locations were selected because the work conducted in Chapter 3 concluded that the AS-MO tool has the promise to benefit resource-constrained farms in these countries.

Participating farms were recruited for this study because the owners and employees were considered early adopters of irrigation equipment; they had used solar-powered drip irrigation—equipment is not widely adopted in their regions—for multiple seasons [78, 28]. Early adopters were recruited because these types of potential users are known to provide useful feedback on the design of novel products [119].

The AS-MO tool prototypes were installed on operational farms to simulate real farm conditions. In Jordan, the experiment was conducted on a 0.8-hectare research farm that frequently tests agriculture innovations. The study participants on the Jordanian farm were an irrigation engineer and a local laborer. In Kenya, the experiment was conducted on a 2.8-hectare farm that exports crops to Europe. The study participant on this farm was the farm manager who oversaw all activities on the farm. A unique AS-MO app login was built for each farm, and all study participants were given the credentials for their respective farms in order to receive auto-generated schedules. Both farms' irrigation networks were already outfitted with manual valves to control flow to blocks or sub-blocks, enabling manual operation.

A two-part research approach was implemented to understand how the AS-MO tool prototype performed from two perspectives: from a water savings perspective and from a user-centered design perspective.

4.3.1 Monitoring water savings

To determine water savings, two values were observed over the course of this study: (1) the volume of water delivered when participants use the AS-MO tool and (2) the volume of water delivered in a setting without the tool. Water savings would be realized if less water were used with the AS-MO tool than without. To measure water used in these two case studies, 11 irrigation blocks in Jordan and four sub-blocks in Kenya were placed under the experiment. Each farm also provided “reference” blocks that were irrigated based on conventional, fully manual irrigation practices. In these studies, a successful AS-MO intervention would be demonstrated if the experimental blocks used less water per hectare than the reference blocks. To measure the water used with and without the AS-MO prototype, the farms’ irrigation networks were outfitted with sensors to measure irrigation practices. There was a different configuration on each site.

The experimental setup on the Jordanian farm is shown in Figure 4-3. A flow meter (FMM200-1002 by ProSense, The Netherlands) was installed on the main line, just after the pump, that measured the system’s total flow rate every five seconds while the pump was running. During periods of no flow, the meter recorded a zero value every ten minutes. All flow measured by this meter was delivered to the experimental blocks, so readings from this meter were integrated over time to calculate the volume of water delivered to the experimental side. The total cultivated area of the experimental side was reported by farm employees, and the volume of water delivered was normalized by this value. These data were collected from May 7, 2023, to July 25, 2023.

On the same site, 11 reference blocks were also irrigated using a separate but comparable pump and hydraulic network with the same sensor configuration. These irrigation blocks grew the same crops as the experimental blocks at the same time and had similar soil types, so this side was considered an experimental control. Farm laborers were asked to irrigate the reference blocks using a conventional schedule. The conventional schedule was determined by asking a neighboring farmer how they would irrigate given the crop and weather conditions. The neighboring farmer visited the site several times throughout the study to update their prescribed schedule. For example, for several weeks during the experiment, the conventional schedule was to irrigate each block every other day for a two-hour duration.

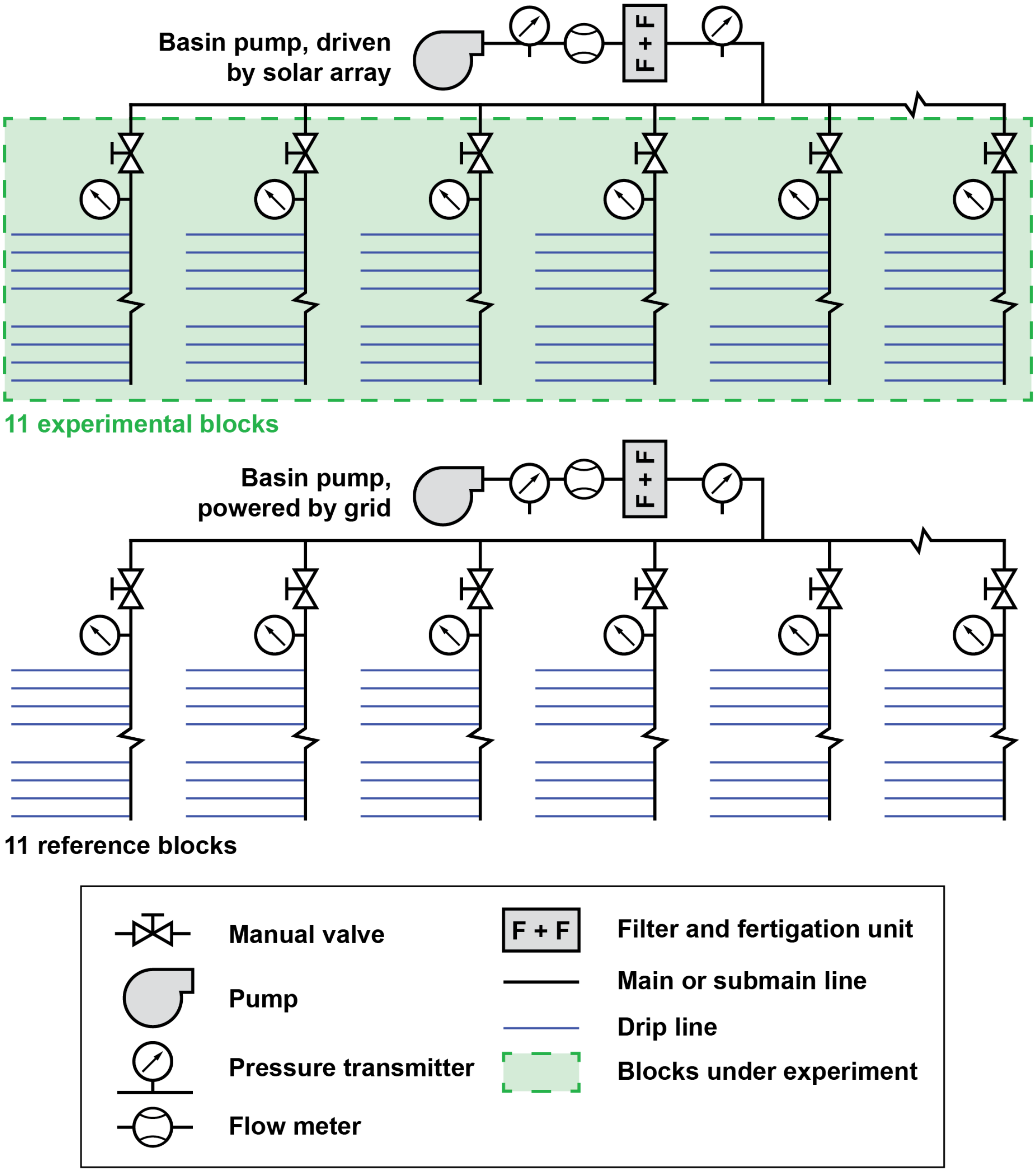


Figure 4-3: Farm layout and experimental setup in Jordan. This farm has 22 irrigation blocks, 11 of which were placed under the experiment (top) and 11 of which were monitored as a reference of conventional irrigation practice (bottom).

In Kenya, the prototype was installed on an active export farm, so the experimental setup was less invasive than on the Jordanian research farm (Figure 4-4). In this case, sensors had to be installed into a previously-designed system without disrupting current operations. The farm had seven irrigation blocks in total, but only one block—consisting of four sub-blocks—was used for the experiment. The other blocks were under strict export regulations, so experimentation was not possible. Due to an unusually prolonged rainy season spanning the spring and summer of 2023, experimental data could not be collected prior to the submission of this thesis. The following paragraphs outline the intended experimental methods in Kenya, and the results will be published in an upcoming journal paper.

To analyze water delivery on the Kenyan site, a time-based analysis, rather than a flow rate-based analysis, will be used. Wireless pressure transducers (G1/4 by Walfront, China) were installed at the end of one drip line in each experimental sub-

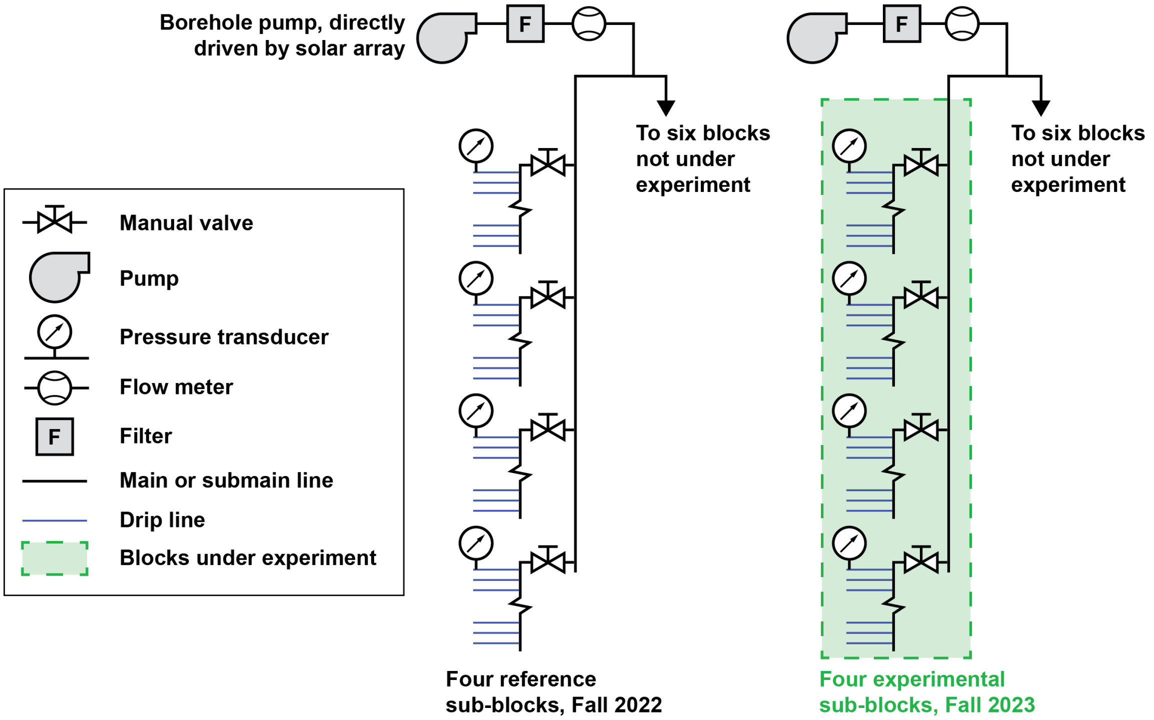


Figure 4-4: Farm layout and experimental setup in Kenya. This farm has seven total irrigation blocks, one of which will be under experiment during the Fall of 2023 (right). The same block was monitored during the Fall of 2022 as the reference block (left). During this season, the farm manager practiced conventional irrigation.

block. When the derivative of these transducers' readings is high, it will be assumed that the valve for that sub-block is open. When the derivative is low, a valve-closing action will be recorded. These timestamps will indicate the start and end of irrigation events, and event durations will be calculated. These durations will be compared to the POWEIr-scheduled durations of irrigation events to understand how much a user's practice differs from the scheduled events.

In the Kenyan case study, the four sub-blocks were monitored for one season in 2022 without the AS-MO intervention, from September 10, 2022, to December 16, 2022. The weather and crop parameters from this reference season were fed into the POWEIr theory to generate daily schedules, but the schedules were not shown to the farm manager. Instead, they irrigated according to their conventional practices. The participants' irrigation practices were measured and analyzed using the methods described above. The differences between the POWEIr-generated schedule and the conventional schedule were calculated for each day. To determine the impact of the AS-MO intervention, the differences observed in the 2022 reference season will be compared to the differences seen in the 2023 experimental season. The two seasons will have different weather and therefore different irrigation demands. However, because the two measured irrigation amounts will be compared to their respective POWEIr-generated schedules, the 2022 season will be considered a valid experimental control.

4.3.2 Monitoring farmer practice and user-centered design of the AS-MO tool

Three specific, user-centered questions were explored. First, *What user behavior explains the water-delivery observations made when participants used the AS-MO tool?* This question is important because there are many reasons why a farmer might use a tool differently than expected. Understanding these reasons can inform the tool's next design iteration, ensuring typical user practice is accounted for. Second, *How could the user experience of the AS-MO tool improve?* When developing a tool, it is important to understand if any of its drawbacks can be mitigated with an improved design. Participants' responses and insights could inform the next iteration of the AS-MO tool's design. Finally, *Do farmers think their irrigation practices are improved with the use of this tool?* There are likely both benefits and drawbacks to using the proposed tool, and it is important to understand if and by how much the benefits outweigh the drawbacks. Users' perceptions of this trade-off ultimately impact the tool's adoption potential.

To answer these questions, farmers were asked to install and use the AS-MO app on their personal devices so they could interact with the prototype. At the beginning of the study, participants were taught by the research team how to use the app over a series of training days using simulated schedules. After training, participants used the app for extended periods of time: from May 10, 2023, to August 18, 2023, in Jordan, and planned for one season in Fall 2023 in Kenya. It was expected that not all irrigation events would be followed according to the POWEIr-generated schedule. To ensure participants experienced the intended flexibility of the AS-MO tool, they were instructed to miss irrigation events if they were not able to perform the actions for any reason. In these cases, participants were asked to note why irrigation events were missed, so the research team could learn these scenarios.

To monitor how farmers used the tool from a quantitative perspective, data regarding user actions were collected for each irrigation event. **Scheduled timestamps**, $T_{S,o}$ and $T_{S,c}$, were recorded when participants were advised by the AS-MO tool to open or close valves, respectively. These timestamps came from the POWEIr-generated schedule. **Confirmed timestamps**, $T_{C,o}$ and $T_{C,c}$, were collected when a participant confirmed an opening or a closing action, respectively, in the app. These timestamps were recorded in the app's backend server. **Measured timestamps**, $T_{M,o}$ and $T_{M,c}$, were recorded when the derivative of pressure transmitters or transducers readings spiked high or low, indicating a recent valve-opening or valve-closing action, respectively. These sensors were installed in each block or sub-block (Figures 4-3 and 4-4). In Jordan, wired pressure transmitters (SPT25-20-0060A by ProSense, The Netherlands) were installed just after the manual valves, and in Kenya, wireless transducers (G1/4 by Walfront, China) were installed in each sub-block at the end of one drip line.

To analyze these data, confirmed and measured timestamps were compared to the corresponding scheduled timestamps for each scheduled user action in five ways. First, if no confirmed or measured timestamp was recorded for a given scheduled timestamp, this was considered a missed event in the app or on the field, respectively.

Second, for each action that was not missed, the differences between scheduled timestamps and the corresponding confirmed and measured timestamps were calculated using

$$\begin{aligned}
\Delta T_{C,o} &= T_{C,o} - T_{S,o} \\
\Delta T_{C,c} &= T_{C,c} - T_{S,c} \\
\Delta T_{M,o} &= T_{M,o} - T_{S,o} \\
\Delta T_{M,c} &= T_{M,c} - T_{S,c}.
\end{aligned}$$

These differences were binned into 5-minute ranges to show how frequently user actions were early or late and by how much.

Third, to understand how opening and closing actions impacted the durations of confirmed and measured irrigation events, the durations of each of these events were compared to the corresponding scheduled durations using

$$\begin{aligned}
\Delta D_{C,S} &= (T_{C,c} - T_{C,o}) - (T_{S,c} - T_{S,o}) \\
\Delta D_{M,S} &= (T_{M,c} - T_{M,o}) - (T_{S,c} - T_{S,o})
\end{aligned}$$

where $\Delta D_{C,S}$ is the difference between confirmed event duration and scheduled duration, and $\Delta D_{M,S}$ is the difference between measured event duration and scheduled duration. These values were binned into 5-minute ranges to show how frequently the durations were short or long and by how much.

Fourth, a similar comparison was made as a percentage of the scheduled event durations using

$$D_{C,rel} = \frac{T_{C,c} - T_{C,o}}{T_{S,c} - T_{S,o}} * 100$$

$$D_{M,rel} = \frac{T_{M,c} - T_{M,o}}{T_{S,c} - T_{S,o}} * 100$$

where $D_{C,rel}$ was the duration of confirmed events relative to the duration of scheduled events, and $D_{M,rel}$ was the duration of measured events relative to the duration of scheduled events. These values were binned into 15% ranges to visualize the impact on durations.

Finally, to understand how $\Delta D_{C,S}$ and $\Delta D_{M,S}$ changed as users became familiar with using the AS-MO tool, these values were totaled for all irrigation blocks on each day of the experiment, and those summations were plotted over time. While the second, third, and fourth analyses did not include missed events, this one did.

To understand farmers' perspectives about the tool's user experience from a qualitative standpoint, participants were interviewed on the phone several times a week throughout the study. Participants were also contacted via WhatsApp messaging or Facebook Messenger. In these interactions, qualitative data about their experiences with the tool were gathered, including why a scheduled irrigation event was not confirmed or measured, why a confirmed or measured action was early or late, if participants had trouble using the tool, and if participants had ideas for design improvements. Appendix E lists example interview questions.

4.4 Results

This section presents the results from the Jordanian case study. The Kenyan experiment is planned for the Fall of 2023, and results will be included in an upcoming journal publication.

4.4.1 Water savings results

After 11 weeks of using the tool on the Jordanian site, there was not a significant difference between water used on the experimental site and on the reference site (Figure 4-5). Water savings were expected but not realized for two key reasons. First, the farmer determining the schedule used on the reference side was an experienced farmer with over 20 years of irrigation experience. They did not represent the average Jordanian farmer who would be more likely to over-irrigate their fields. If the irrigation practices enabled by the AS-MO tool were compared to the irrigation practices of an average or novice farmer, water savings would be more likely to be realized.

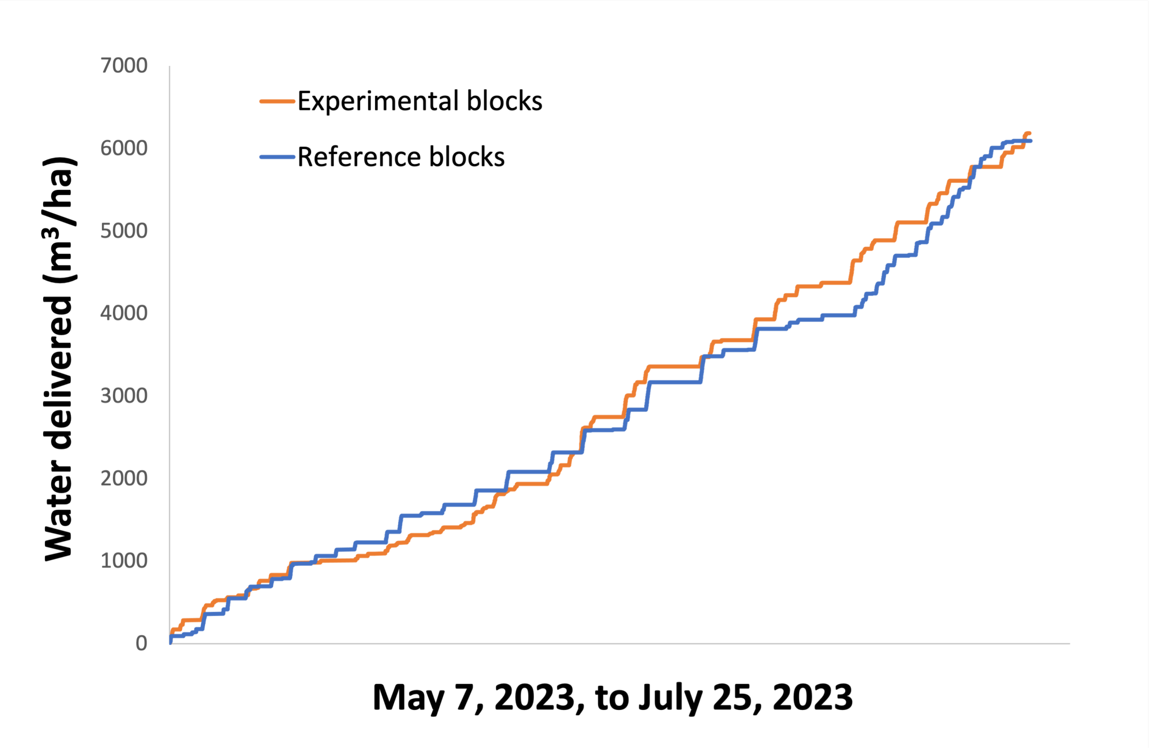


Figure 4-5: The cumulative water used on the Jordanian site over the course of the experiment. When comparing the experimental blocks to the measured blocks, significant water savings were not realized due to two important factors.

Second, the crop growth coefficients—important inputs to the POWEIr theory—estimated for the crops in this case study were 30% high, which meant the automatically-scheduled event durations were 30% longer than ideal. This error caused users to deliver more water than was necessary. If these crop coefficients were corrected, significant water savings would have likely been demonstrated.

4.4.2 User-centered design results

Quantitative user behavior

The AS-MO prototype was found to perform successfully from a user-centered perspective. Over the course of the study, there were 590 scheduled irrigation events (Table 4.2). For 93% of these scheduled events, users' confirmations aligned with what was measured on the field (e.g., confirmations and measurements either both indicated action had been taken or both indicated no action had been taken). The POWEIr theory relies on users' correct reporting of their actions in order to schedule future irrigation events, so it is important this number be high. There were 40 instances when users likely forgot to confirm actions in the app or forgot to open valves but they remembered the other action. This scenario was expected, but the occurrence was low, meaning the tool was used successfully.

Table 4.2: Of the 590 scheduled irrigation events, the number of events confirmed by participants with the AS-MO tool and the number of measured events observed on the Jordanian experimental site from May 7, 2023, to July 25, 2023.

Irrigation event type	**Number**	**Percentage of scheduled events**
Confirmed actions and measured actions	301	51%
No confirmed or measured actions	249	42%
Confirmed actions but no measured actions	25	4%
No confirmed actions but measured actions	15	3%

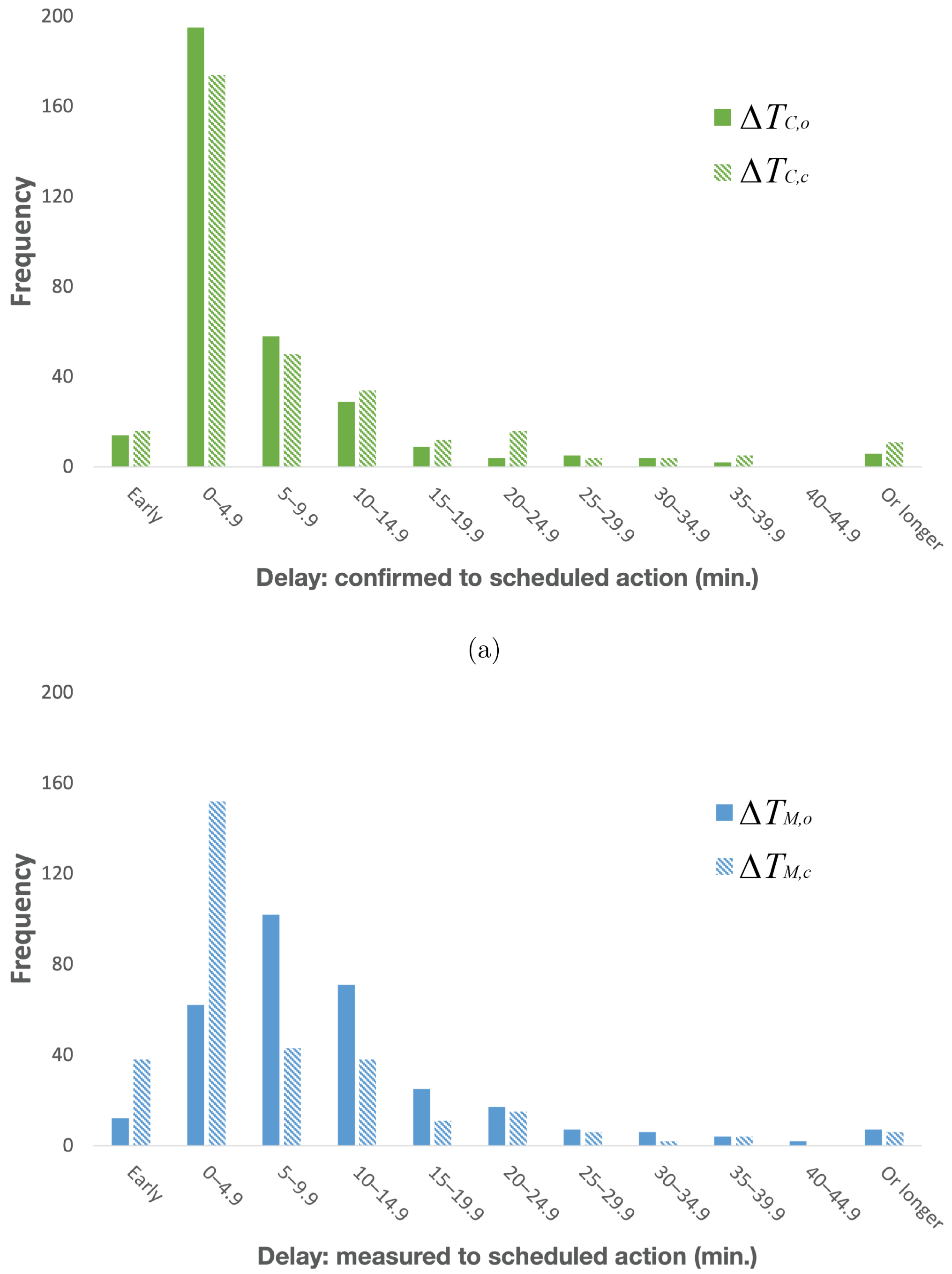
Over 50% of the time, users both confirmed actions and these actions were measured. It was expected that not all events would be both confirmed and measured because farms are busy settings. The work conducted in Chapter 3 suggested the need for irrigation schedules to have a degree of flexibility, so this response rate was considered successful. The specific reasons why scheduled irrigation events were not confirmed or measured are discussed further in the following section.

As expected, confirmed and measured opening and closing actions were not observed at exactly the scheduled times. These actions were more frequently late than early (Figure 4-6). However, they often occurred close to the corresponding scheduled times. In Figure 4-6a, 60% of confirmed opening actions and 53% of confirmed closing actions were recorded within five minutes after the corresponding scheduled time. Opening and closing confirmed actions have similar frequencies within each bin range, suggesting that users respond similarly to both direction types in the app.

In contrast to the confirmed actions, there was an observable disparity between the measured opening and measured closing actions. Measured opening actions most frequently fell in the 5–9.9-minute bin (32% of all measured opening actions) while 48% of measured closing actions were observed within five minutes of the corresponding scheduled times. There are two possible explanations for the disparity observed between the measured opening and closing actions. First, in all irrigation systems, it takes a certain amount of time after a pump is turned on for water to fill the hydraulic network. This filling delay was not accounted for in the POWEIr scheduling theory, so the pressure transmitters may not have sensed the action exactly when participants opened a valve. To mitigate this effect in the future, the filling time for each section could be measured during calibration and input into the POWEIr theory. This time could be added to each scheduled event to ensure crop water demand is met.

Second, users are more likely better primed for closing actions than they are for opening actions. For example, if a user is far from the irrigation block when a scheduled event starts, they will have to walk some distance to manually open the valve. When a closing action is scheduled, users have just completed an opening action, so they are more likely to already be near the valve. This is especially true for short irrigation events. A potential mitigation strategy could be to send opening action notifications earlier than is currently designed in the AS-MO app. Earlier notifications could allow users the travel time they may need to reach the manual valve.

For both measured and confirmed actions, there are very few early actions observed. This suggests that push notification reminders to users' phones, a key feature



(a)

(b)

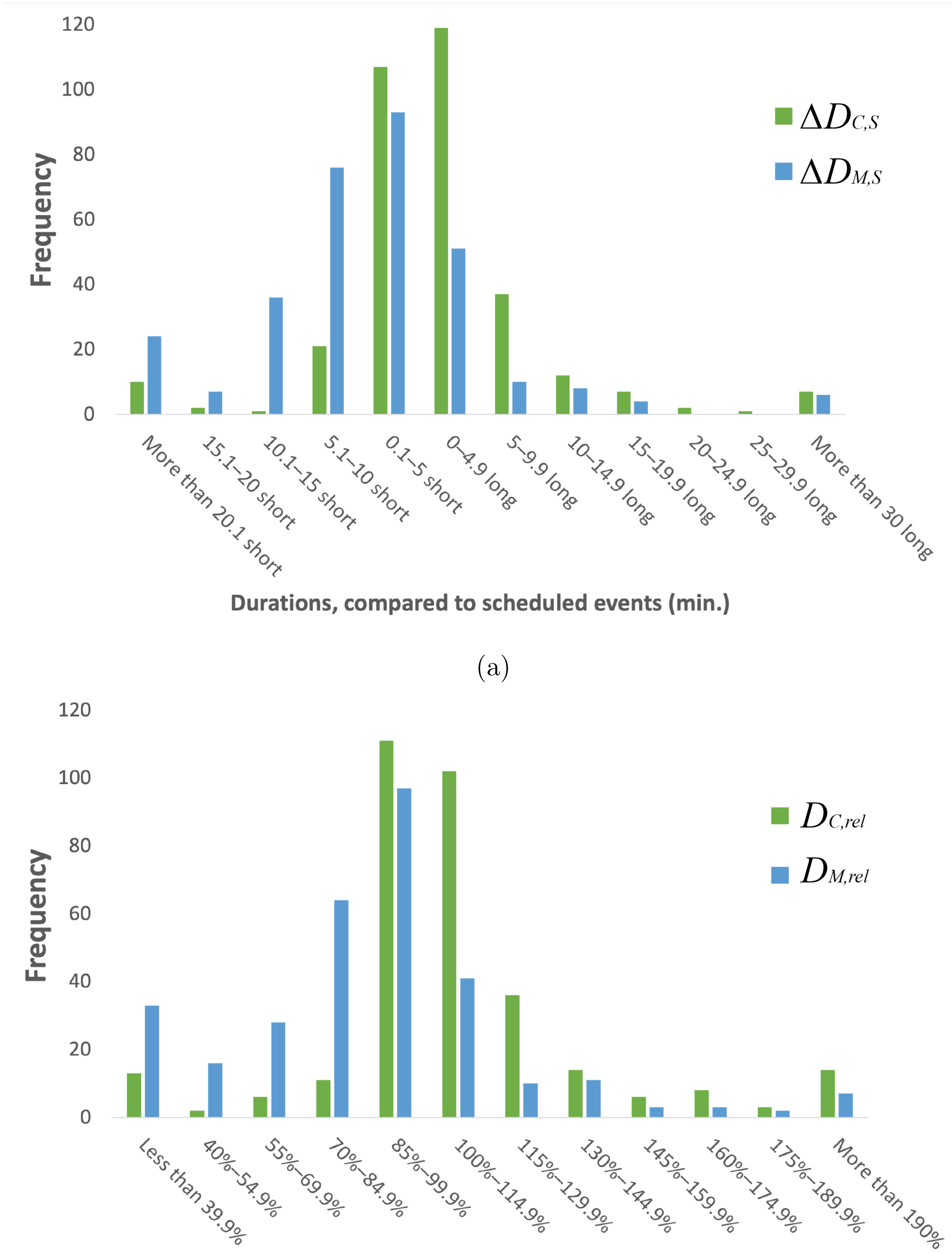
Figure 4-6: Frequency of how early or late (a) confirmed actions and (b) measured actions occurred, compared to scheduled actions. Confirmed actions and measure closing actions occurred most frequently within five minutes of the scheduled action. The majority of measure openings occurred within 10 minutes of the scheduled action.

of the AS-MO tool and UX, are critical to its success. If users did not have notifications, they would need to continuously check the AS-MO app schedule page for upcoming actions. This could be frustrating for users, and without notifications, the rate of delayed actions would be expected to increase.

The late and early actions translated to duration differences between confirmed and measured irrigation events and scheduled events (Figure 4-7). For all events, $\Delta D_{C,S}$, $\Delta D_{M,S}$, $D_{C,rel}$, and $D_{M,rel}$ most frequently within the 5-minute bins and the 15% bins, respectively. These results further demonstrate the success of the AS-MO tool and UX in this case study because farmers can realize the full efficiency benefits of the POWEIr theory if they irrigate close to scheduled events.

Several user behavior patterns can be observed in Figure 4-6. First, the mean of all $\Delta D_{M,S}$ data points falls below zero minutes while the mean of $\Delta D_{C,S}$ data points falls above it. This shows that confirmed events were longer on average than scheduled events while measured events were shorter on average, a result that further supports the explanations discussed regarding Figure 4-6b. Measured events may be short in duration because the hydraulic network takes time to fill when valves are first opened or because study participants were more likely ready to close valves than open them. It is unclear why confirmed durations tend to be longer than scheduled events. This is important to mitigate because the POWEIr theory assumed more water was delivered than was the case. If this happens too frequently, crops could become water stressed. Further investigation into user observations could provide insights into this result.

Additionally, there were a minimal number of very long irrigation events observed (the rightmost bins in Figure 4-7). In these cases, participants may have forgotten to confirm a closing action in the app, forgotten to close the manual valve, or forgotten both actions. It was expected that users might forget to confirm closing actions, so the POWEIr scheduling theory was designed to assume no irrigation event would extend until midnight. If a valve was confirmed as open at midnight, the theory would assume no water delivery instead of several hours of water delivery. This solution avoids any potential water stress to the crops. If the opposite scenario occurs and a user confirms



(a)

(b)

Figure 4-7: Frequency of how short or long confirmed durations and measured durations occurred, compared to scheduled durations, reported (a) in minutes, and (b) as percentages of the scheduled duration. Confirmed and measured durations occurred most frequently within five minutes and 15% of scheduled durations.

a closing action in the app but forgets to close the valve, the crops would receive more water than expected. This would in turn decrease the water savings, but the crops would not experience stress.

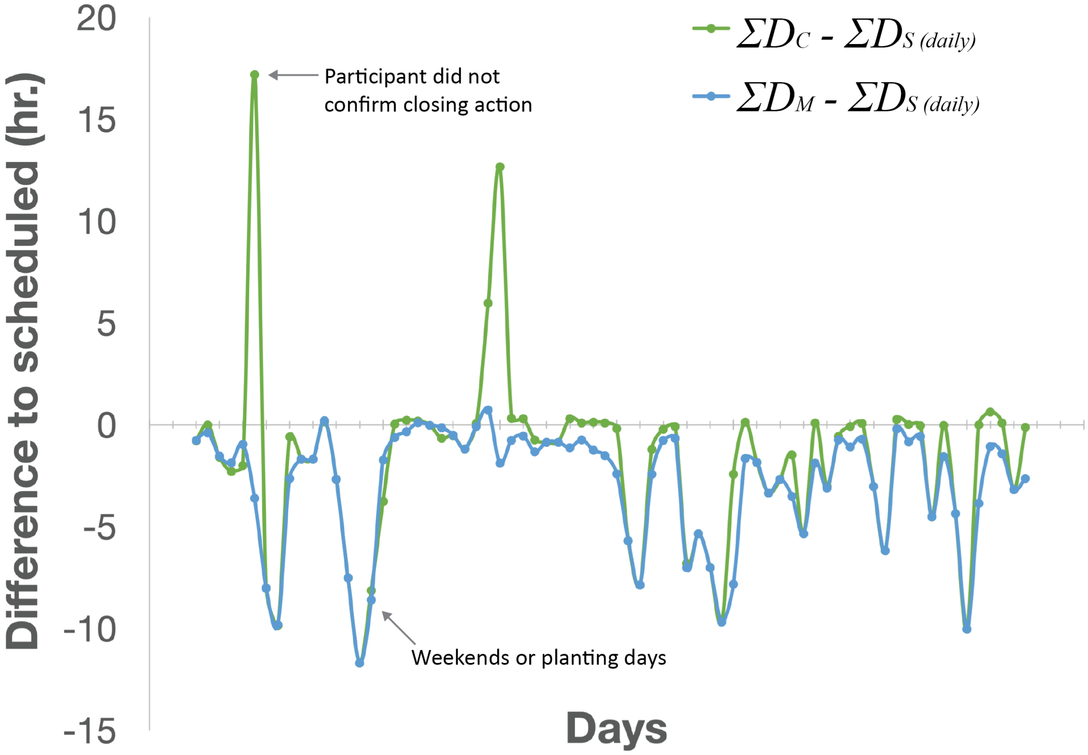


Figure 4-8: Daily confirmed (green) and measured (blue) irrigation durations compared to scheduled irrigation durations from May 7, 2023, to July 25, 2023. This figure includes both confirmed and missed irrigation events and shows that the AS-MO tool enabled participants to follow the schedule over time even if they missed irrigation events for several days. Outlier data points provide insight into missed events (visualized when both lines are very low) and forgotten confirmations (visualized when the green line is very high).

Figure 4-8 shows how confirmed and measured durations compared to scheduled durations over the course of the experiment. There are two large spikes in the green line in the first half of the experiment. On these days, participants did not confirm closing actions, so the tool recorded that a valve was open for many hours. As mentioned above, the POWEIr theory accounted for this user error by assuming no irrigation rather than assuming many hours. Other than these errors, the two lines track well, with confirmed events often slightly longer than measured events.

This result aligns with previous results. Further, there are many days for which the two lines are near zero, indicating participants implemented an efficient, POWEIR-generated schedule. There are also several days for which both lines are negative by several hours. This occurred on days when farmers could not irrigate because it was a weekend or because there were other farm activities that took laborers away from irrigation (e.g., planting or harvesting), so they missed irrigation events. Even after several days of many missed events, both lines always return to near zero. This observation suggests the AS-MO tool is able to help farmers return to the automated schedule, even if they do not irrigate for several days. Of course, depending on the size of the irrigation system and energy storage, this may not always be possible. Further work can be done to understand how much user error should be expected and designed for when building new irrigation systems.

Qualitative user behavior results and suggested design updates

In interviews, interview participants claimed that their irrigation practices were improved when using this tool. In the middle of the study, one participant noted that the crops on the experimental side were growing just as well as those on the reference side, meaning that the volumes delivered to the experimental side were appropriate to not stress crops. Further results on the impact on crop yield will be explored in an upcoming journal paper that validates the POWEIr theory.

The two participants in Jordan claimed that in general, the AS-MO tool and app were easy for them to learn and use, a result consistent with the trends seen in Figure 4-8. They did mention two specific ways the AS-MO could be improved. First, one participant said the notifications were helpful but that they also set their own alarm 15 minutes before each irrigation event was scheduled to start. They did this at the beginning of the day when they reviewed the schedule for the first time. This result implies that the notifications were useful but that the timing could be improved. A future iteration of the AS-MO app could allow users to set how early they would like to receive notifications prior to scheduled actions. This change could potentially decrease the frequency of late actions. Second, one participant asked if the app was available for iOS devices. During the study, this participant started using an iPhone, but for this iteration, the app was only designed for Android devices. This meant the participant had to carry their old phone to use the AS-MO tool. The next iteration of the AS-MO app should be designed for both platforms to expand its potential reach.

This work sought to understand *why* farmers might miss events, so the late, early, or missed actions shown in Table 4.2 were not considered failures of the AS-MO tool. Table 4.3 summarizes the most common reasons why participants did not follow the automatically-generated irrigation schedule. For each observation, suggestions for how to address these issues are also provided. Future iterations of the AS-MO tool could be designed with these results in mind, increasing the chance of user adoption.

Table 4.3: Common reasons why irrigation actions were late, early, or missed and the resulting design suggestion for the next iteration of an AS-MO tool.

	Reason irrigation action was late, early, or missed	**Suggested update to AS-MO tool design**
1	Scheduled irrigation events conflicted with participant's other commitments (e.g., weekends, prayer time, scheduled farm maintenance, planting or harvesting events)	The AS-MO app could provide users the ability to "blackout" times they know they will not be available for irrigation. These times could feed into the POWEIr theory, and the theory could schedule around the times farmers are unavailable.
2	Participant remembered to open or close the manual valve but forgot to record that action with the AS-MO tool	The confirmed valve status in the AS-MO app could control power to the pump. If participants can only turn on the pump using the app, they will be more likely to confirm actions in the app. Because the phone may be unavailable occasionally, users must have a backup option to turn on their system.
3	If a participant wanted to irrigate a block that was not scheduled, there was no event on the app schedule with which they could confirm opening or closing actions	The AS-MO app should allow users to confirm actions for irrigation blocks that are not scheduled on a given day. If users do not have this feature but still choose to irrigate, the POWEIr theory would not account for this irrigation amount in future calculations.
4	Participant's mobile device lost network connectivity, so confirmed actions were not sent to the cloud, and therefore, were not accounted for by the POWEIr theory	The AS-MO app should store critical information internally so it can send data to the cloud when network connectivity is restored. Alternatively, if the scheduling algorithms can run on hardware located on the field, continual connection to the cloud may not be necessary. Users' phones could instead connect to a local network to send and receive updates.
5	Participant's mobile device lost network connectivity, so notifications were not sent to participants throughout the day	The AS-MO app should send notifications from the app directly and not rely on the cloud throughout the day. If this feature were implemented, a user's phone would only need network connectivity once at the beginning of the day to download the daily schedule and other critical information.

4.5 Discussion

The first objective of this work was to demonstrate that irrigation with an AS-MO tool uses less water compared to conventional irrigation practices. While this case study in Jordan did not demonstrate water savings, this result led to important insights. One difficulty in accomplishing water savings without stressing crops is inputting accurate farm parameters into the POWEIr model. In this study, the crop growth coefficients were entered into the tool about 30% high, causing the scheduled event durations to be 30% longer than ideal. The POWEIr theory relies on these parameters—typically reported as ranges that depend on several factors—to calculate water demand. A limitation of automatic scheduling, it is not always known which value should be used for these coefficients. Because the proposed AS-MO tool combines automatic scheduling with manual operation, this UX ensures a farmer will always be on the field. The scheduling flexibility provided to farmers enables them to verify and address any inaccuracies in the automatic scheduling caused by calibration errors.

Increasing the accuracy of correct crop parameters is necessary for farmers to use an AS-MO tool and realize water savings. Regional agricultural research institutions often publish parameters they have empirically measured, but not all crop species in all regions have been measured. Future work can be done to understand how accurate these parameters must be in order for the POWEIr theory to generate water-saving irrigation schedules that do not stress crops.

While water savings were not demonstrated in this case study, these results still indicate the potential savings the AS-MO tool can afford. Initial results validating the POWEIr theory show that it can enable farmers to use 44% less water when paired with solenoid valves[1]. The results of this thesis show that farmers can use an AS-MO tool to deliver successful operation of an automatically-generated schedule. Combining these insights suggests that an AS-MO tool would deliver the water-saving benefit of the POWEIr theory if the correct parameters were input into the tool.

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[1] This value is an initial result of the POWEIr theory validation conducted in Morocco, as described in Section 4.2.1. This farm uses solenoid valves, so there was no user error, and the crop growth coefficients used for this experiment are more accurate.

Correct parameters are functions of crop species and local conditions. As researchers improve the available parameters, the accuracy of the auto-generated schedules will continue to improve, increasing the potential for farmers to realize water savings with an AS-MO tool.

The second objective of this work was to demonstrate that farmers use an AS-MO tool as intended in a real farm setting. Figures 4-7 and 4-8 demonstrate this was the case on the Jordanian farm. The durations of confirmed and measured events on the field most frequently fall within 15% of the corresponding scheduled durations, meaning the farm largely realized the efficiency benefits of automatic scheduling. The differences between measured and confirmed durations compared to scheduled durations could be further improved with updates to the AS-MO tool. For example, the POWEIr scheduling theory does not account for the time it takes to fill the hydraulic network, a scenario that likely decreased the measured durations observed in this study. Further, the AS-MO tool could allow users to adjust the timing of push notifications. If opening notifications arrived earlier than the start of an event, users might be more ready for these actions on time.

Participants' confirmed and measured actions tracked well over time, often delivering similar amounts of water as the AS-MO tool scheduled (Figure 4-8). These results indicated that the AS-MO tool was robust to user error and helped farmers return to an efficient schedule, even after several missed events. Because farmers are busy, users should not be expected to perform all scheduled irrigation actions as advised by the tool. This was the case in this study, confirming that one benefit of the POWEIr theory is that it is adaptable; it has the ability to compensate for missed events and user errors. Further, the AS-MO tool

Overall, the AS-MO tool was used successfully by participants. While participants accurately confirmed actions only 51% of the time, results show the performance was close. There was a high percentage of missed events, but the majority were missed for logistical reasons (e.g., weekends, holidays, planting or harvesting days, or planned maintenance). A number of last-minute skips occurred as well. For example, cell service was lost, other work activities took longer than expected, or the participants forgot to check their phones. Still, these last-minute skips were rare. If the suggested changes in Table 3.4.3 were implemented, it would be expected that the percentage of missed events would significantly decrease. From there, further testing could be done to understand more about the nature and impact of these last-minute skips. This low-cost, easy-to-use tool was designed to be more accessible to resource-constrained farms than conventional precision irrigation solutions. If used in the way demonstrated in this work, such a tool could enable a higher adoption of water-efficient irrigation schedules, like those generated by the POWEIr theory, while relying on the low-cost manual valve hardware that is already present on many EA and MENA farms.

The final objective of this work was to determine the features of an AS-MO tool that farmers find most valuable and to establish what added or changed features could increase its adoptability. Both quantitative (Figure 4-6) and qualitative results suggest that the push notifications were helpful to participants. Notifications sent slightly earlier before scheduled actions could improve users' ability to follow the auto-generated schedule. Table 4.3 introduces five suggested design updates to the AS-MO tool that have the potential to improve the UX and minimize the number of missed scheduled events. These updates were determined by testing with just two study participants, so further work must be done to understand if additional updates are needed.

An important objective of evaluating the AS-MO tool is to assess its adaptability among target users, but that objective was not addressed in this work. The participants in this study agreed to use the tool for the course of this experiment and were not given the option to disadopt it. To evaluate the adoptability of this tool, testing with a greater number of farmers is necessary, and study participants should be given the option to not adopt or to revert to their prior irrigation practices if they believe the tool does not meet their needs. Prior work [75, 108, 12] and results discussed in Chapter 3 highlight the importance of using demonstration farms to encourage adoption. An evaluation of the AS-MO tool adoption could incorporate demonstration farms. In this scenario, demonstration farms (on the order of 10) would be equipped with the AS-MO tool. Farmers on the demonstration farms would use the tool in earnest, and neighboring farmers would be invited to see its impact on these farms. These neighboring farmers would then have the opportunity to adopt or not adopt the tool on their own farms. Understanding these farmers' adoption choices would provide data on the potential adoptability of the AS-MO tool.

This work only followed two participants, with a third one planned. Increasing the number of farmer perspectives evaluated will confirm if the results found in this work can be expected for the majority of users or not. This work assumed that the selected participants—farmers in Jordan and Kenya—represented small- to medium-scale MENA farmers and medium-scale EA farmers, respectively. Evaluating the AS-MO tool with farmers in other EA and MENA countries would validate this assumption. Because the study participants were early adopters of solar-powered drip irrigation, this work does not provide information on how users who are new to this technology might use an AS-MO tool. Expanding the study to include new adopters would provide insights on these types of users.

The results of this case study provide value to both engineering practitioners and other researchers in the field. First, irrigation equipment designers can see the successful demonstration of a semi-manual/semi-automatic tool—an architecture that could inspire new product concepts. The proposed AS-MO tool and UX brought precision irrigation practices to the studied Jordanian farm. Equipment designers and engineers working in these contexts could implement similar semi-manual/semi-automated approaches for other applications, like fertigation or landscaping.

Further, researchers who work in resource-constrained contexts could learn from how the AS-MO design process was conducted. Figure 4-9 illustrates the process taken by the research team to develop this technology. Iterations of the UX were conducted in parallel to iterations of the POWEIr scheduling theory. Learnings from these two design cycles informed each other. The researchers developing the UX elucidated user needs and communicated them to the researchers developing the theory who, in turn, informed on the theory's technical capabilities and limitations. All researchers believed their work has a higher potential for impact because of these interactions. A product design process that incorporates both technical development and user-driven understandings in this way is known to be successful [111]. However, it is not always followed in academic research, with users sometimes being addressed only at the end of design processes. This can lead to low adoption rates and limited impact of technical innovations. The work described in this thesis demonstrates the value of testing a transformative technology's user experience in parallel to testing its technical aspects.

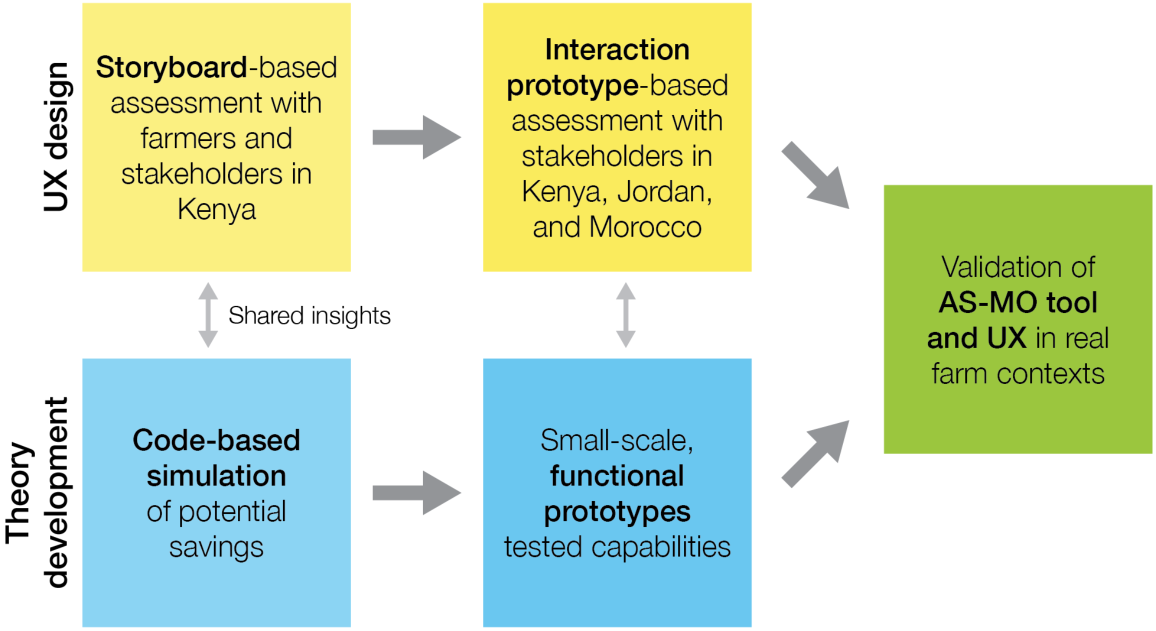


Figure 4-9: Design process followed for the AS-MO UX and the POWEIr scheduling theory the tool uses.

4.6 Conclusions

This work aimed to evaluate an AS-MO tool and UX in EA and MENA farm settings. To do this, two functional AS-MO tool prototypes were designed to deliver a realistic UX to study participants. One prototype was installed on a Jordanian farm and one on a Kenyan farm. Employees on the Jordanian farm used the tool for 11 weeks, and the Kenyan participant is planning to use it during the Fall 2023 season. To evaluate the potential water savings a farmer might realize with an AS-MO tool, participants' irrigation practices with the tool were compared to conventional irrigating practices. Due to an error in crop input parameters, significant water savings compared to conventional irrigation was not demonstrated in the case study presented in this thesis. However, the results of this work show promise for future pilots of this tool when these parameters are corrected.

To understand how farmers use the tool, participants' valve-opening and valve-closing actions on the field were compared to the actions scheduled by the tool. Results showed that participants used the AS-MO tool successfully. For 93% of the 590 scheduled events, farmers correctly confirmed their actions or inactions in the AS-MO app. When responding to irrigation actions, participants confirmed 56.5% of actions within five minutes of the scheduled time. Sensors on the field measured a different behavior. While 48% of all closing actions were measured within five minutes of the scheduled time, the majority of measured opening actions fell in the 5–9.9-minute bin. This result indicates there was a difference between opening and closing actions on the field. Further work should seek to incorporate this pattern into the AS-MO tool's design. It was shown that the AS-MO tool was robust to user error because it enabled farmers to follow an automatically-generated schedule over the course of the experiment even when farmers followed its instructions for only 51% of events. Overall, a majority of the confirmed and measured durations fell within 10 minutes or 15% of the scheduled durations, demonstrating the successful use of the AS-MO tool.

The preliminary water usage result of the POWEIr theory validation conducted in Morocco suggests that the tool can bring the water-efficiency benefits of precision irritation when used correctly. The results of this work indicate the AS-MO tool can be used correctly by farmers. Therefore, the AS-MO tool and UX have the potential to be used successfully by farmers on resource-constrained farms.

In qualitative interviews, participants suggested several design updates that could improve the AS-MO UX. For example, the AS-MO app sent participants notifications as irrigation events started, but one participant set their own alarms to notify them 15 minutes earlier. Adjusting the app's notification timing could further improve users' response time. Additionally, the research team observed issues with the prototype functionality: irrigation events were scheduled when participants were unavailable, participants occasionally forgot to confirm actions on the AS-MO app, participants did not experience all the scheduling flexibility an AS-MO tool could enable, and participants' devices occasionally lost network connectivity. This work proposes suggestions for how to address these concerns in the next iteration of an AS-MO tool.

Future work should integrate and test all of these suggestions. Additional testing with more farmers could elucidate further insights and verify the ultimate adoptability of an AS-MO tool. If adopted by EA and MENA farmers at scale, the proposed AS-MO tool has the potential to increase the prevalence of water-efficient irrigation practices on resource-constrained farms, contributing to sustainable agriculture in these two regions.

Chapter 5

Conclusions

The overarching aim of this thesis was to design a technology that could enable resource-constrained farmers in EA and MENA to adopt sustainable irrigation equipment and practices. First, a needs assessment of the EA agricultural market provided insights into distinct segments and farmers and their corresponding needs (Chapter 2). A techno-economic assessment was conducted to reveal the most promising system architectures for each segment. Given the insights gleaned regarding the values of medium-scale contract farmers, the concept for an AS-MO tool and UX was developed (Chapter 3). This concept was evaluated through storyboards and an interaction prototype to ensure it closely met farmers' needs. At this stage, the concept was also assessed with small- to medium-scale MENA farmers to understand how it could best meet their needs in addition to the needs of EA farmers. Finally, incorporating these findings, the design of the AS-MO tool and UX was updated (Chapter 4). A successful field demonstration of this tool and UX was conducted on a Jordanian farm. In addition to the findings summarized at the end of each chapter, the overarching conclusions of this thesis are:

- There exist four distinct market segments of farmers in EA: traditional smallholders, semi-commercial smallholders, medium-scale contract farmers, and remote farmers. The profiles detailed in this work can help individuals and groups who serve EA farmers understand the specific differences between the segments.

- Each segment, driven by their agricultural goals, values different features and outcomes of irrigation systems. In sum, traditional smallholders would value a system that uses PV panels + manual irrigation. In the semi-commercial smallholder market, users would value a PV panel + butterfly sprinkler-based system. Finally, for medium-scale contract farmers and remote farm owners, a PV panel + NPC drip-based system is a promising architecture. These results motivate areas of potential innovation in the irrigation equipment space.

- Medium-scale farmers in Kenya and small- to medium-scale farmers in Jordan in particular value the semi-manual/semi-automatic features that an AS-MO tool could deliver. Interviewees noted that automatic scheduling could improve their irrigation decision-making, saving them time and money. They claimed they preferred to realize this benefit while continuing to implement manual operation on their farms because manual valves are familiar and inexpensive. This result demonstrates the adoption potential of an AS-MO tool among these types of farmers.

- When tested by participants for eleven weeks, participants used the AS-MO tool prototype as expected. By count, 93% of the automatically-scheduled irrigation events were measured and confirmed in alignment. Of the events that were carried out on the field, a majority had durations within 15% of the scheduled durations. These results imply that farmers can adopt the water-efficient practices enabled by the AS-MO tool described in this thesis. User error was anticipated, and results show that the AS-MO tool was robust to the errors observed in this study.

- While water savings were not demonstrated in this experiment due to an error in the input crop parameters, the results point to anticipated savings in future pilots. First, the underlying scheduling theory used in the AS-MO tool is being concurrently validated in a separate experiment, and early results show that the theory enables 44% less water usage than conventional irrigation. Second, this work demonstrated that users can successfully use the AS-MO tool and UX.

Combining these results suggests that the water-efficiency benefits of precision irritation can be realized on farms when an AS-MO tool is adopted.

- Throughout all iterations of the AS-MO tool and UX described in this thesis—storyboards, an interaction prototype, and a functioning prototype—farmers and key market stakeholders provided valuable insights as to how to improve its design. Many of these suggestions were incorporated into the functional prototype described in Section 4.2. Other suggestions are documented in this thesis for future development.

5.1 Future directions

In this thesis, an AS-MO tool and UX were designed and successfully demonstrated on a farm in Jordan. However, this work elucidated further areas for innovation that could promote sustainable agriculture in EA and MENA. Specifically:

1. Chapter 4 detailed the experimental procedure planned for an AS-MO demonstration in Kenya. This work is planned for the Fall of 2023. Because the contexts are different, insights from this case study are expected to differ from the learnings of the Jordanian case study. These results will inform how EA farmers might use an AS-MO tool differently than MENA farmers.

2. Findings from the Jordanian case study in Chapter 4 suggested several design updates that could mitigate errors observed in this demonstration (Table 4.3). These specific recommendations should be incorporated into the next iteration of an AS-MO tool and UX, and that iteration should be tested with a greater number of farmers.

3. The POWEIr theory behind the AS-MO tool is concurrently being validated on a farm in Morocco to ensure it delivers water-efficient schedules without damaging crops. After this validation, the theory will likely be improved. It is recommended that the next iteration of the AS-MO tool include this updated

theory. To ensure adoption of this tool, it will be important to gather user feedback on this updated theory. Users' perceptions of the reliability of the tool's auto-generated schedules will be key to market penetration of the AS-MO tool.

4. Chapters 3 and 4 addressed the medium-scale contract farmers, but Chapter 2 outlined three additional market segments of EA farmers and potential technology solutions targeting each segment's specific needs. Future development could focus on traditional smallholders, semi-commercial smallholders, and remote farmers. Addressing all segments will ensure that the majority of EA farmers have sustainable irrigation solutions designed to specifically fit their needs and values.

Appendix A

Example interview questions asked to farmers and stakeholders during market segmentation

Below are sample questions asked to participants asked during the interviews described in Section 2.2.

A.1 Questions asked to farmers

Not all questions were asked to all farmers. Depending on farmers' situations, relevant questions were selected.

1. How long have you been farming?
2. How long have you been farming on this farm?
3. How old are you?
4. How large is your farm?
5. Do you have other plots?
6. How large are your other plots? How far away are they?

7. What crops do you grow on this plot? Other plots?
8. How many people are in your household?
9. How many adults/children in your household?
10. Does anyone else use your water? How many people? What do they use it for?
11. Do you sell water to anyone else?
12. Do you have livestock? How many?
13. How much water do your animals drink?
14. Tell us about your irrigation system.
15. How long have you used it?
16. What do you like about it? What do you dislike?
17. Where did you first see this pump system? How did you learn about it?
18. Why convinced you to purchase/use this system?
19. Have you had any maintenance issues with your pump? How were they fixed?
20. Tell us about your irrigation schedule now. How many hours per day and days per week?
21. How did you irrigate before?
22. How much time did it take you to irrigate before?
23. How do you know when to stop watering?
24. How were you trained on drip irrigation?
25. How was drip irrigation installed on your farm?
26. What do you like about drip? Dislike?

27. Have you experienced clogging of the drip emitters?
28. Do you use a filter?
29. Have you noticed uniformity issues with your system?
30. Have animals bitten your drip lines and caused problems?
31. What is your water source?
32. What is the depth of your well?
33. Did someone install the well for you? How much did it cost? How long did it take?
34. What else do you use the water for in addition to irrigating?
35. Do you drink the water?
36. What was the cost of your pump/irrigation system?
37. Did you take out a loan to pay for the system? What are the details of that loan?
38. What was your income previously from produce? What is it now?
39. Have you noticed an increase in yield?
40. Do you have trouble selling your produce?
41. What work did you do previously?
42. Do you have other current sources of income?
43. If you had more money for your farm, what would you buy next?
44. If there were a pump that was twice as slow, but half the cost, would you buy it?
45. How many max hours would you spend irrigating?

46. What is the biggest challenge you face in farming?
47. What are your future plans for your farm?
48. What fertilizer do you use? What pesticides? How much?
49. If your system has a battery, what do you use the battery for other than irrigation?

A.2 Questions asked to stakeholders

Not all questions were asked to all stakeholders. Depending on their expertise, relevant questions were selected.

1. Who are your main customers/clients? Are they buying irrigation equipment for the first time? Or are they repeat customers?
2. How does someone first contact you?
3. What is the process like from the first time you meet with them until they have their irrigation system installed?
4. What are your best-selling irrigation products/pumps?
5. When a customer is purchasing an irrigation system/equipment, what kinds of questions do they ask you?
6. Why might a farmer choose drip irrigation? Why might they not choose drip? What would they choose instead?
7. When do you recommend PC or NPC drip? Do farmers have a preference between the two?
8. Do you find that many farmers have similar needs (in terms of size and capacity)?

9. What are the general trends in irrigation products or practices that you recommend to farmers?
10. What are the general trends in irrigation products or practices that are being adopted at high rates? If there is a mismatch in what you recommend and what you see, why might that be?
11. What are some of the biggest challenges you see farmers face?
12. What are the most promising ways you think to solve these challenges?

Appendix B

Details of market segment profiles

This appendix gives details that were used to build the farmer market segment profiles shown in Section 2.2.2.

B.1 Traditional smallholder

Responses of farmers interviewed revealed that the main farming motivation for traditional smallholders is to grow food for their families. All farmers interviewed in this market segment consumed the majority of the food they produced. Of the 10 traditional smallholders interviewed, all farmers sold only a small portion of their produce in local markets. Instead, these subsistence-focused farmers primarily producing food for in-home consumption. As a result, irrigated areas in this market segment tended to be the smallest. A typical irrigated area among this segment was 0.125 ha, though non-irrigated cultivated land and non-cultivated holdings were typically larger. In an interview, members of the One Acre Fund, an NGO that provides input services to smallholders in EA, corroborated that this amount of land alone could sustain an average family. Farmers reported growing at least four crops to meet their family's dietary needs. These crops varied by region and included maize, cassava, teff, cabbage, onion, and kale. In addition, many farmers reported a desire to grow a wide variety of crops in the future, demonstrating the value they placed on crop diversity.

Traditional smallholders tended to have experience with only one irrigation method, *the one they were using at the time of the interview. However, the low penetration of irrigation among farmers with <2 ha (0.7–2.3% across EA) suggests that even this minimal experience is above average and that the vast majority of traditional smallholders have minimal or no irrigation experience [32].* This lack of irrigation penetration may be related to the remoteness of these farmers, all of whom lived far from cities. Agricultural innovation has been found to be lower in remote regions where disseminating agricultural information is difficult [93]. This barrier is consistent with interview responses, which confirmed that both information access and training opportunities were limited among traditional smallholders.

Of the EA traditional smallholders who do irrigate, most rely on manual irrigation [78]. This is known to be labor intensive and many farmers reported having to carry water from a distant water source to their field. In Zambia, where Water4 (an NGO) recently installed solar-powered submersible pumps on local farms, one farmer reported that his previous manual irrigation practice required over four hours each day to fill a 630L tank from a lake source 300m away. This experience was typical among smallholders who previously relied on manual irrigation. Other farmers reported that manual irrigation was not only tiring, but also dangerous. Several farmers in this area raised concerns about crocodiles attacking humans during water collection, reporting that at least one farmer per year is killed by crocodiles while fetching water. While interviewed farmers no longer faced these issues, these experiences are likely to be typical of smallholders in the region who continue to use manual irrigation.

Attitudes towards manually-powered pumps with low capital costs, such as the treadle pump, revealed both the high value placed on low-cost irrigation and the high physical toll of supplying the water manually. A 66-year-old farmer in Ethiopia reported operating his treadle pump for at least an hour each day and feeling exhausted by the effort. In interviews, several high-level executives at a company that sells treadle pumps, also remarked how tiring their pump is to use. These results suggest that a large value add to these farmers' daily lives would be an irrigation system that does not rely on human power. Some traditional smallholders use small fuel pumps, and they expressed how valuable it was to not have to carry water.

Attitudes towards risk and income generation patterns suggest that traditional smallholders tend to be very risk adverse and would value a system that they know they could pay for in 2–3 seasons' worth of profits. These smallholders use income source diversification as a risk management strategy [91]. For EA countries, the Food and Agriculture Organization of the United Nations reports that 43–62% of small family farm income comes from crop production while the remainder comes from other sources, suggesting that they are not willing to rely solely on high risk agriculture for income [32]. This was consistent with behavior demonstrated throughout the interviews. Four of the 10 interviewed traditional smallholders noted additional sources. This diversification of income suggests an increased risk aversion and an increased need for financial guarantee. Traditional smallholders think about their farming future 2–3 seasons out. This short payback time frame reported by farmers suggests that they want to have a guarantee that an irrigation system would be paid back in that time period. If not, they may risk diving deeper into poverty. Multiple farmers who were still paying back a system expressed deep concern over potentially defaulting on loans. Farmers are not the only stakeholders who want to see a quick return on their investments. In interviews, NGOs that provide loans to traditional smallholders stressed the need for farmers to be able to pay for a system in less than one year because they do not trust farmers to pay back longer loans. The interviewed MFIs do not currently provide loans to traditional smallholders for irrigation equipment because it is too risky for the MFI. They have in the past, but too many farmers defaulted, leaving the MFIs to refuse new farmers who fit this profile. Many farmers in this segment are below or just above the poverty line [91, 29], and their pattern of income diversification suggests that they are unlikely to invest all their additional income or savings into one system, even if that system increases their agricultural productivity. A high-performing, inexpensive system that can be paid back in 2–3 seasons would provide value to both traditional smallholders and the stakeholders who serve them.

Increasingly more farmers in this segment have home lighting [77] and cell phones [24], two products the interviewed farmers valued if they had access. One traditional smallholder in Ethiopia commented on a standalone lighting product he owned. He paid 3500 birr (122 USD) for it and believed it was worth the cost; for reference, a treadle pump costs 170 USD [65]. Current irrigation systems that serve traditional smallholders do not incorporate USB ports for these valuable features, but our results suggest that the majority of traditional smallholders would value this add-on.

B.2 Semi-commercial smallholder

The semi-commercial smallholder was likely a traditional smallholder at one time. Now, they have moved away from subsistence farming, seeing how they can start a small farming business. Compared to the traditional smallholder, they are more willing to invest both time and money in equipment that has a promising return on investment because they have seen past success in agriculture. Thirteen of the 14 interviewed semi-commercial smallholders used PV-powered irrigation systems sold by Futurepump or SunCulture. This indicates farmers' willingness to invest in more expensive equipment. Depending on the specifications and added features, these systems cost between 600–1550 USD, which farmers pay for over 2–3 years [104, 39].

Compared to traditional smallholders who have diverse income sources, farmers in this market segment are more focused on farming as their main income source. Therefore, they are able to dedicate more irrigation time per day than traditional smallholders can. Five of the interviewed farmers spent at least 4 hours irrigating each day, with three of them spending over 8 hours. Of the nine who spent less than 4 hours irrigating per day, seven used NPC drip irrigation. They spent 1–2 hours monitoring the irrigation, and then they could let it run while they focused on other tasks, meaning the farms were being irrigated for longer than 4 hrs/day. It is estimated that semi-commercial smallholders will spend up to 6 hrs/day irrigating, especially if they do not need to continuously monitor it.

Not all semi-commercial smallholders were once traditional smallholders. City dwellers who move to the country for retirement can also fit this profile. This was the case for three of the 14 interviewed farmers. Their motivations were to sustain their own diets and to supplement their retirement funds by selling the remaining produce. In these cases, the farmers were still confident they could make their monthly payments even if they had a few unsuccessful seasons.

Interviewed semi-commercial smallholders grew largely the same types of crops as traditional smallholders, with a slightly higher focus on fruits and vegetables over grains. Fruits and vegetables are all higher value crops than grains like maize, teff, or cassava [33]. Given commonalities between all interviews, it is estimated that semi-commercial smallholders sell 30% of their product in a local market or to a middleman who transports it to a nearby city. One farmer who has been farming for almost 25 years did not sell any product until he purchased one of SunCulture's PV-powered system: the RainMaker2. Now, he estimates he sells between 50–100 kg of produce each week during the harvest season.

Semi-commercial smallholders are quick to implement new agriculture techniques when they have access to the right resources. The majority of interviewed farmers in this segment had access to some form of professional training. Certain RainMaker2 models have a television bundled into the irrigation product. This television comes preloaded with Shamba Shape Up, a TV series that teaches improved farming techniques [73]. One farmer said this content was his favorite part of his RainMaker2 product. After watching the tutorials, he was able to confidently raise chickens to expand his agriculture business. Other farmers were trained to use their irrigation equipment by representatives from the distributor. One farmer said she received about an hour of training on her Futurepump PV-powered irrigation system when it was installed. Another farmer had inexpensive, non-pressure compensating (NPC) drip irrigation lines installed in his greenhouse. He was trained how to use them for daily uses but not how to flush them to prevent emitter clogging. Two farmers mentioned that they were curious about drip irrigation, but did not yet know how to use it. While there is a need for better training in this market, the current training that these farmers receive is better than what the traditional smallholders typically have access to. This means they are able to adopt more advanced irrigation methods, like drip irrigation.

Farmers in this segment derive value from small home appliances, like televisions and pressure cookers, and they are willing to pay for these items. Pressure cookers allowed farmers to cook warm food faster than their previous methods. Televisions gave farmers a source of entertainment in addition to the Shamba Shape Up tutorials. In interviews, SunCulture leadership stressed the success of bundling a television with their irrigation systems. At the time of the interview, their highest-selling product was the RainMaker2 with ClimateSmart™ Battery + TV. These systems had such high sales that SunCulture has since started selling a system with just the battery, television, and home lighting: the ClimateSmart™ Battery + TV [104]. In interviews, farmers asked for agricultural products that could pair with their systems as well. A popular request was a chaff cutter, followed by an egg incubator. This suggests that these types of appliances, in addition to the home lighting and phone-charging, would increase the likelihood that semi-commercial smallholders adopt an irrigation system.

B.3 Medium-scale contract farmer

Medium-scale contract farmers run full-time farming businesses to feed the growing cities in EA [59, 82, 85]. They cultivate medium-sized farms in peri-urban areas. The interviewed farmers irrigated between 1.2–8 ha, but they owned more, between 2.4–20 ha, suggesting there is an opportunity to expand irrigation on these farms. In support, one stakeholder who had previously served contract farmers claimed there were still many underserved farmers who owned 2–6 ha. To supply food to nearby cities, these farmers have contracts with middlemen who deliver their produce to urban supermarkets, hotels, universities, or airlines, for example. Farms are within a few hours' drive to these destinations, so there is a chance they have grid connections. However, these connections may not be reliable as outages are common [14].

Farmers in this market segment invest in their businesses. Intending to sell >95% of their produce, they cultivate high value crops like tomatoes, herbs, and fruit. Two farmers reported the costs of their irrigation systems: 18,500 USD for a system that irrigates 8 ha and 30,000 USD for a system that irrigates 1.2 ha. This second system cost includes the cost of drilling a 300 m deep borehole. Farmers in this segment invest in equipment, planning on a 5–10-year timeline.

Medium-scale contract farmers employ seasonal and full-time laborers who irrigate, weed, plant, and harvest. Because farmers have this additional help, they are willing to spend the whole solar day irrigating, an estimated 7 hrs. Five of seven interviewed farmers said their irrigation systems run for longer than 5 hrs each day.

Medium-scale contract farmers have advanced irrigation experience compared to the smallholders, but they still experience challenges. Five of the seven interviewed farmers used NPC drip irrigation, and all of them were familiar with the technology. Farmers liked that drip irrigation let them irrigate without much oversight. They or a laborer could open one section of the network and then perform non-irrigation tasks for 30-60 minutes until they needed to switch to another section. Stakeholders confirmed this benefit, but noted that that drip only works well for farmers who have learned how to use drip effectively. Farmers and stakeholders alike noted that emitter clogging was a large drawback of this technology. Sediment can collect in the small emitter features, blocking the flow of water. Farmers need to follow proper filtration and flushing regiments to avoid this, but not all do.

Because these farmers focus on selling their produce, the appearance and size uniformity of their crop is important. Pressure-compensating (PC) drip is typically preferred for increased crop uniformity because it regulates the flow of all drip emitters in a network, but stakeholders who design irrigation systems for this market segment said they always recommend NPC drip over PC. They do recommend PC drip to floriculturists who have even higher uniformity standards. However, for medium-scale contract farmers, system designers do not see how the added value of PC drip outweighs the higher equipment cost. To overcome the uniformity drawbacks of NPC drip, irrigation systems are designed with small sections (about 0.2 ha), with laterals no longer than 30 m. For comparison, in regions that have higher PC emitter adoption rates, like India, laterals can be up to 75 m long. Current 0.2 ha sections are irrigated for only 30 minutes at a time, which means section valves are turned on and off frequently. Longer laterals could reduce labor needs as irrigation sections could be larger. Having larger sections means having fewer sections and fewer people monitoring the irrigation schedule changes.

B.4 Remote farm owner

The remote farm owner lives in a city, but owns or rents land in a nearby peri-urban region. They farm as a hobby or as a way to make a supplemental income while investing in the land. While the remote farm owner may be involved in making big decisions about the farm, they are not present on a daily basis. Instead, they hire farm managers and laborers to run the farm for them. One Nairobi-based remote farm owner visits his farm almost every weekend and pays 4–5 laborers to tend during the weeks.

The remote farming market segment is an emerging one and not all problems with managing a farm remotely have been solved, so there is risk involved for the owners. For example, one stakeholder who sells seedlings to farmers has had several remote farming customers. He recommends they avoid this model, predicting they will "be taken for a ride." For example, one of his customers bought chemicals for their farm. Their laborers claimed to have sprayed them, but in reality, the chemicals were resold. The quality of the of crops were evidence that the plants did not get appropriate care. The Nairobi-based remote farm owner agreed that his laborers do not show the same quality of work when he is not on site.

Farmers in this segment have capital to invest in irrigation systems, but they do not intend for farming to be their main income source. A second interviewed remote farm owner has been running a real estate company for 10 years. He had no knowledge of farming but saw this as a growing business opportunity. At the time of the interview, he was still in the process of setting up the farm, but he had high hopes based on the success he has seen with other remote farm owners in his network.

Appendix C

Elaboration on irrigation method and energy source parameters in Tables 2.3-2.4

C.1 Irrigation methods

C.1.1 Manual irrigation

Manual irrigation, using buckets or handheld hoses to deliver water to a field, is one of the most commonly used irrigation methods among EA smallholders [95]. One reason for this popularity is its low cost, an estimated capital cost of 10 USD that needs replacement every two years [7]. While inexpensive, manual irrigation is very labor intensive, limiting the area that can be irrigated in a single day by a single farmer. Farmers can only irrigate one plant at a time, so the estimated maximum area they can irrigate in a day is 0.2 ha. Assuming no additional labor is hired, these estimations give manual irrigation an equipment cost of 50 USD/ha.

Manual irrigation can deliver water-usage benefits because farmers walk with and constantly monitor their irrigation amount. Farmers are likely to only water the base of the crops and not the space in between, so the estimated water factor for manual irrigation is 0.5. Manual irrigation takes very little pressure head to operate, an estimated maximum of 1 m [89]. If a bucket is used, the head needed is 0 m. If a hose is used, no more than 1 m of head is needed.

A key drawback of manual irrigation is that it is a physically demanding job for farmers as they must continually walk with the equipment. If they are using buckets, they are also tasked with carrying the water load. This drawback is analyzed further when discussing results from the farmer interviews.

C.1.2 Flood and furrow irrigation

Flood irrigation, covering the entire field with water, or furrow irrigation, filling furrows between crop beds with water, are two traditional irrigation methods commonly used by smallholders and medium-scale farmers in EA [105]. These irrigation methods use very little equipment, so the low cost makes them a popular option. In addition to a pump, only a 50 m hose pipe is needed to direct the water flow, an estimated cost of 25 USD/ha with a lifetime of two years [7]. This hose pipe would not need more than 5 m of pressure head.

A big drawback to flood and furrow irrigation is the high water usage, with an estimated water factor of 1.0 [9]. The entire field must be covered with water for flood irrigation, and about half of the field area is covered for furrow irrigation. Still, the furrows must be filled with water, so overwatering is common, bringing the estimated water factor to 1.0 for both methods. According to a key stakeholder who sells irrigation products to farmers, a second drawback to flood or furrow irrigation is the significant amount of skill needed to prepare the field, which could deter farmers with little irrigation experience.

C.1.3 Butterfly sprinklers

Butterfly sprinklers are increasing in popularity among smallholders in EA, and they are included in irrigation kits like SunCulture's RainMaker2 series [104]. For this analysis, it is assumed that a farmer uses one set of five sprinklers that they move throughout their field. In this set up, a farmer moves the sprinkler heads every 30 to

60 minutes.

This butterfly sprinkler set operates at 10 m of pressure head and costs an estimated 26.5 USD with a lifetime of two years. According to irrigation system designers, butterfly sprinklers cost 0.30 USD per unit. A 50 m hose to connect the sprinklers to a pump costs 25 USD [7]. For this estimation, it is assumed that the five sprinklers operate in parallel and that one sprinkler plus one 50 m hose operates in a range centered around 10 m of pressure head [84]. Because they are operated in parallel, the entire set of five sprinklers also operates at 10 m of pressure head.

Two drawbacks of sprinklers are their high water usage and their need for farmer labor. Sprinklers distribute water to the entire field with a water factor of 1.0 [9]. In the assumed set of five movable sprinklers, there is labor involved, but less than in manual irrigation.

C.1.4 NPC inline drip irrigation

According to a stakeholder who owns an irrigation equipment company in Kenya, NPC inline drip irrigation is commonly used by farmers in EA who focus on selling a large volume of crop. Drip irrigation delivers water to rows of crops through a network of stationary main and submain pipes and lateral lines. At the base of each plant, an emitter bonded to the inside of the lateral line allows water to flow. Because drip only delivers water to the root bases, the estimated water factor is 0.5 [9].

Netafim's Streamline™ X, a popular emitter globally, is used as a representative NPC emitter which operates at a range centered around a 10.2 m pressure and a 2.2 L/hr flow rate [80]. Non-pressure compensating drip emitters do not regulate the flow of water when varying pressure is applied. This means that, on a flat field, emitters at the end of a lateral line will be lower in flow than emitters at the beginning of that line. It also means that a graded field will result in non-uniform flow rates.

A 0.2 ha section of NPC drip operates at 14 m of pressure head and costs 2400 USD/ha in EA with an equipment lifetime of three years. Stakeholder interviews suggest that typical NPC drip sections in Kenya were 0.2 ha, or 30 m by 67 m. They have 100 30 m-long lateral lines with 0.3 m crop spacings. The operation of this 0.2

ha pipe network was simulated using a systems-level model [96, 49], showing that it works at a pressure head of 14 m. Interviews with stakeholders showed that NPC drip irrigation (including lateral lines, emitters, submain and main pipes, and valves) in Kenya costs an estimated 2400 USD/ha. It is expected that this equipment has a lifetime of three years before the plastic lines degrade or crack [80].

C.1.5 LE PC inline drip irrigation

LE PC inline drip irrigation is a method that is not yet widely used, but shows promise in the region [114]. It relies on novel emitters designed by the MIT GEAR Lab that have the potential to save 42–54% in pumping power over standard-pressure emitters for surface-water systems [102, 101]. Unlike NPC emitters, PC emitters use silicone membranes to regulate water flow once an activation pressure is reached. The consequence of this flow rate regulation is increased flow uniformity throughout the field, which leads to increased crop size uniformity. The GEAR Lab has recently developed LE PC emitters that activate at 1.5 m head with 2.2 L/hr flow rates. Compared to conventional PC emitters like Netafim's UniRam™ RC that activate at 5.0 m [81], LE PC emitters show promise for reducing the capital cost of solar-powered systems or the operating costs of grid- and fuel-based systems [102].

A 0.2 ha section of LE PC drip operates at 5.9 m of pressure head and costs 6000 USD/ha with a lifetime of ten years. LE PC drip is expected to cost a similar amount as conventional PC drip costs, 6000 USD/ha. One interviewed stakeholder who sells drip equipment estimates that PC lines cost roughly 2.5 times more than NPC in Kenya. This discrepancy is due to the thicker pipe walls of PC lines and the added silicone membranes in each emitter. LE PC drip equipment is expected to have a similar lifetime as conventional PC drip: ten years [81]. Like NPC drip, the water factor of LE PC drip is 0.5.

C.2 Energy sources

C.2.1 PV panels

PV panels are becoming an increasingly popular energy source across all EA market segments as panel prices decrease [56]. The 2019 Global LEAP Awards estimates the price of solar panels in EA to be 0.81 USD/W [27]. This cost estimate was confirmed as a reasonable estimate with stakeholders at Illumina Africa, a PV panel installation company based in Nairobi, Kenya. The lifetime of a solar panel is estimated to be 20 years [76].

Solar panels are viable options for many regions in EA, rural or peri-urban, because EA records high solar irradiances for the majority of the year [94]. PV panels are one of the most sustainable energy sources, so they are being promoted by NGOs, companies, and governments. For example, import taxes are waived on PV panels used for agriculture in Kenya [41].

C.2.2 Grid electricity

Grid electricity is an option for some EA farms that are close to cities and have existing grid connections. In Kenya in 2015, 17.1% of rural households and 73.0% of urban households had grid connections, suggesting that farmers in peri-urban areas may also have access to grid electricity [63]. Electricity costs in Kenya are 0.06 USD/MJ [45]. Installing new grid connections can be prohibitively expensive to farmers in EA [14], so it was outside the scope of this study to consider new connections.

C.2.3 Fuel

Fuel is currently the most popular external energy source for irrigation among smallholders in EA [22]. Fuel prices fluctuate by time and region, but are estimated to be 0.03 USD/MJ, from 1.025 USD/L of diesel [44] and an energy density of 36 MJ/L. Capital and replacement equipment costs are not applicable for grid or fuel energy sources because the recurring cost of purchasing energy dominates any estimation.

Appendix D

Storyboards of AS-MO tool & UX and sample questions used during farmer and stakeholder interviews

Below are the storyboards shown to EA farmers, as described in Section 3.4. After each storyboard are several sample questions asked when it was shown.

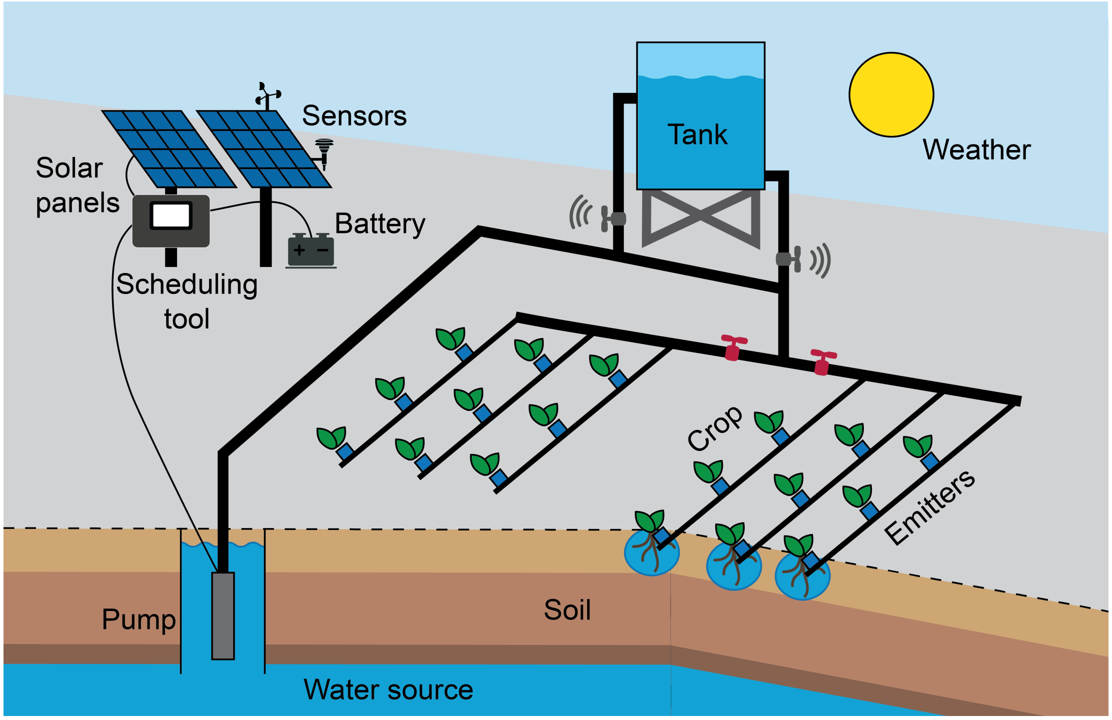


Figure D-1: The first storyboard shown to farmers depicts what a solar-powered drip irrigation system with an AS-MO tool might look like on a farm. Systems could have a pump that feeds from a water source. Water can be stored in a raised tank and drained to a network of pipes and drip lines, or it can pump directly to the drip network. Drip lines have emitters that deliver water directly to the root zones of crops. Solar panels could power the system, and energy could be stored in batteries and/or the raised tank. The scheduling tool could be mounted somewhere central, like under the panels. Sensors are also mounted centrally, and they record weather data.

Sample questions asked with the above storyboard:

1. Do see how this relates to your farm?

2. Do you have any questions?

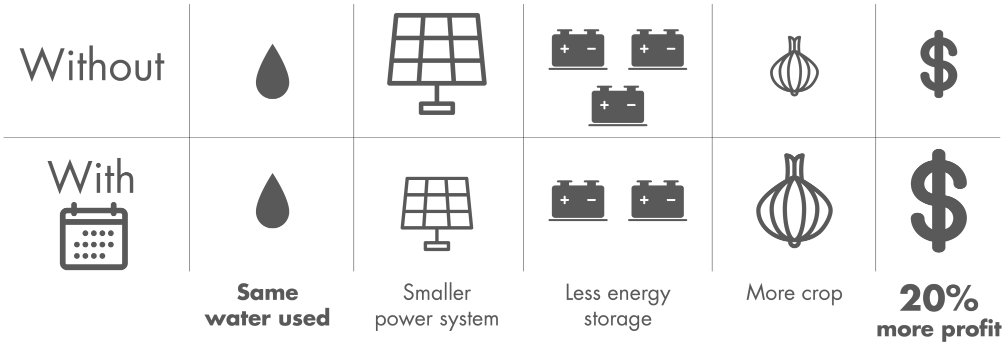


Figure D-2: The second storyboard shown to farmers gives an overview of the predicted value that the scheduling tool could bring to farmers, comparing a system without the tool (top row) to one with it (bottom row). While maintaining water used, the tool allows for smaller power system sizes, less energy storage, and an increase in crop production. These savings manifest in an estimated 20% profit. A similar storyboard was shown to farmers who needed to save water. This alternate storyboard instead showed that the scheduling tool could grow the same amount of crops with a reduced volume of water and a smaller power system.

Sample questions asked with the above storyboard:

1. Does this tool sound like something you would install on your farm?
2. Does this tool sound like something that might convince your neighbors to install solar?
3. Do you think the benefits of this tool sounds believable?
4. Do you have any questions?

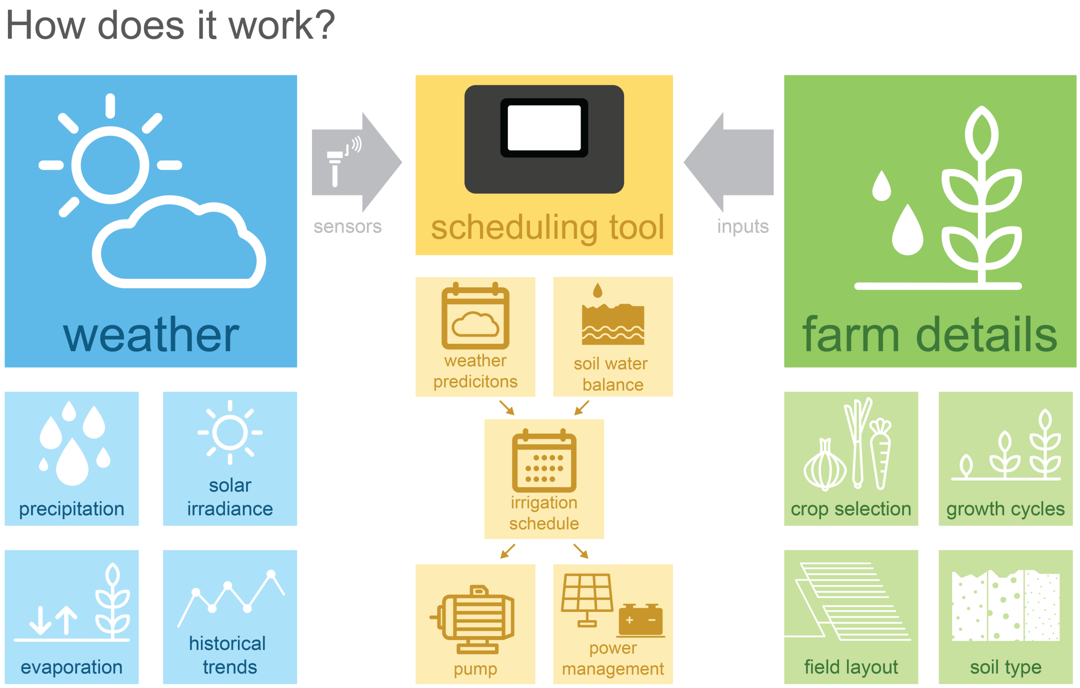
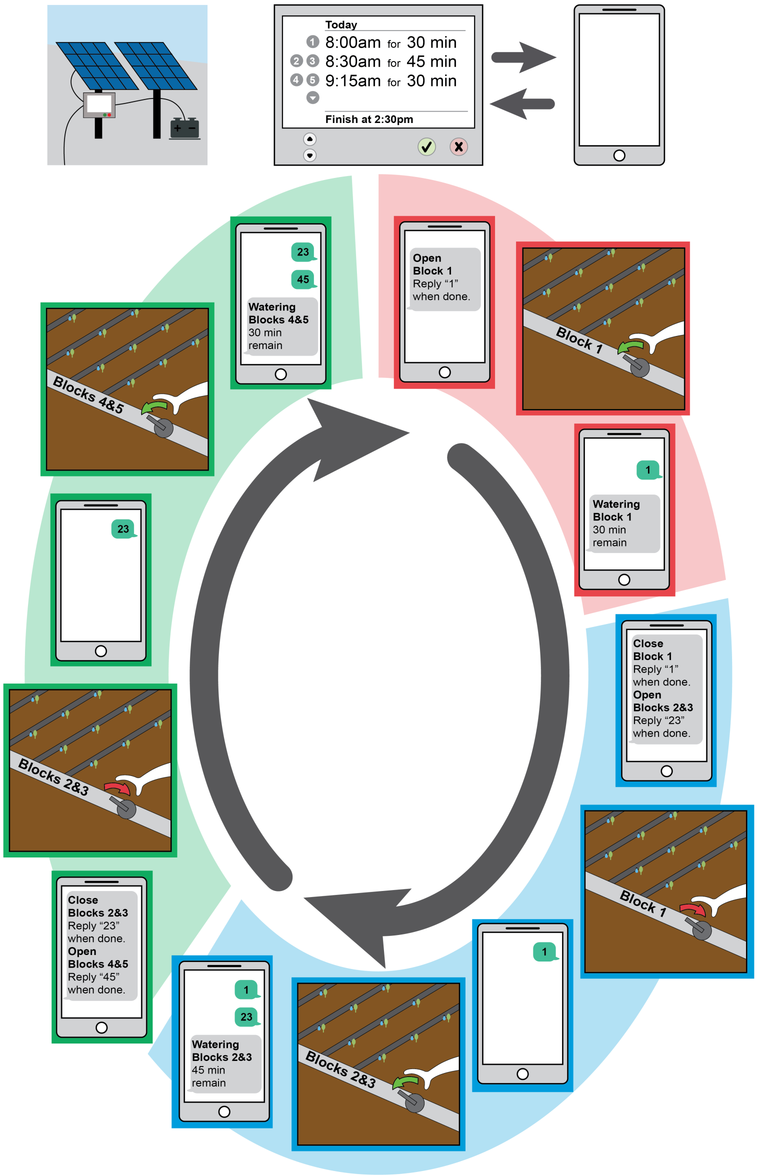


Figure D-3: The third storyboard shown to farmers provides an overview of how the scheduling tool works. It takes in sensed and historical weather information, such as precipitation and solar irradiance, to calculate evapotranspiration. The tool also factors in key farm details—including the crops that are grown on the field and the drip irrigation layout—that are input by the farmer. With these inputs, the scheduling tool can make short term weather predictions and can calculate the soil water balance to determine the optimal irrigation schedule from agronomy and system energy management standpoints. This schedule can instruct farmers how to operate their pump and manage the available power.

Sample questions asked with the above storyboard:

1. Are there any important details missing that the tool should measure?
2. What details are you most excited about that the tool measures?
3. Do you have any questions?


Today
① 8:00am for 30 min
② ③ 8:30am for 45 min
④ ⑤ 9:15am for 30 min
Finish at 2:30pm

Open Block 1 Reply “1” when done.

1

Watering Block 1 30 min remain

Close Block 1 Reply “1” when done. Open Blocks 2&3 Reply “23” when done.

1

1

23

Watering Blocks 2&3 45 min remain

Close Blocks 2&3 Reply “23” when done. Open Blocks 4&5 Reply “45” when done.

23

23

45

Watering Blocks 4&5 30 min remain

Figure D-4: The fourth storyboard shown to farmers provides a depiction of how farmers might interact with the proposed AS-MO tool using SMS reminders. At the beginning of the day, the tool tells the farmer their irrigation schedule. The farmer has the option to accept the schedule or make modifications. Once the approved schedule starts, the tool sends an SMS to the farmer’s cell phone with the first instruction (e.g., “Open Block 1. Reply ‘1’ when done”). The farmer follows these instructions, confirming when they have completed the task(s). After the appropriate amount of irrigation time, another SMS is sent to the farmer, telling them the next direction (e.g., “Close Block 1. Reply ‘1’ when done. Open Blocks 2 & 3. Reply ‘23’ when done”). This interaction cycle continues throughout the day until the irrigation schedule is finished.

Sample questions asked with the above storyboard:

1. Do you think a tool like this would help solve any of your challenges? Why or why not?
2. What are some issues you anticipate with this tool?
3. This tool uses valves that you have to change manually. We are also considering automated valves. Do you have a preference? Why?
4. In the case of a fully-automated system, when might you want a manual override?
5. Do you like this solution more than your current practices? How much? Why or why not?
6. Do you have any questions?

Appendix E

Sample questions used during AS-MO validation experiment interviews

Below are sample questions asked to participants asked during the interviews described in Section 4.3.2.

1. Do you feel confident in the schedule this app builds? Why or why not?
2. How often do you find yourself adding time to the schedule it builds? Subtracting time?
3. When you add or subtract time, what makes you decide to do so?
4. What information do you think the tool is missing that you are able to see on the field?
5. When you receive a notification from the app, do you tend to respond immediately, delay, or tell someone else to take care of the action?
6. Do you use the weather page often? If so, how do you use it?
7. Do you use the crop page often? If so, how do you use it?
8. Does the app make sense?
9. Are you having any trouble using the app?

10. What do you find most helpful about the app?

11. What do you find most frustrating about the app?

12. What would you change to make the app better?

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