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A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL POWER ENGINEERING

Design and Field Evaluation of a Solar-Assisted Irrigation Control System for Smallholder Farms in the Nile Delta

Tasmim wa-Taqyim Nizam al-Tahakkum bi-al-Rayy al-Mudaam bi-al-Taqah al-Shamsiyyah lil-Mazari al-Saghirah fi al-Delta

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To my parents, whose patience outlasted every deadline,
and to the farmers of the Delta, whose fields taught me
more about engineering than any lecture hall.

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Finally, I thank my family and colleagues in the graduate research group for their encouragement throughout the two years of this study.

Youssef Ahmed Mansour
Cairo, July 2026

Abstract

Thesis Abstract

Smallholder farms across the Nile Delta rely predominantly on fixed-schedule surface irrigation, a practice that has changed little in decades despite mounting pressure on water allocations. This thesis presents the design, implementation, and field evaluation of a low-cost, solar-powered irrigation control system that combines real-time soil-moisture sensing with a rule-based scheduling controller to reduce water consumption without compromising crop yield.

The proposed system integrates capacitive soil-moisture probes, a photovoltaic power supply sized for continuous unattended operation, and a microcontroller-based valve actuator communicating over a low-power wide-area network. A scheduling algorithm combines sensor readings with a five-day evapotranspiration forecast to generate irrigation commands, and a fallback timer schedule ensures operation continues safely if sensor or network faults occur.

The system was deployed across six 0.5-feddan plots of cotton and maize in Kafr El-Sheikh Governorate over a single growing season. Compared with matched control plots under conventional scheduling, the controlled plots achieved a mean water-use reduction of 27.4% with no statistically significant difference in yield ($p = 0.31$). Levelized cost of the controller hardware, amortized over an assumed five-year service life, was estimated at EGP 940 per feddan per season. The results indicate that low-cost, solar-powered precision-irrigation controllers are technically and economically viable for smallholder contexts in the Delta, and the thesis concludes with recommendations for a larger multi-season field trial and integration with the national agricultural extension service.

Keywords: precision irrigation, soil-moisture sensing, photovoltaic control systems, smallholder agriculture, Nile Delta, water-use efficiency.

Arabic Abstract

Mulakhkhas al-Risalah

Nizaman li-al-tahakkum bi-al-rayy bi-al-taqah al-shamsiyyah li-al-mazari al-saghirah bi-al-Delta, yajmau bayna istishar rutubat al-turbah wa-tanbuat al-taqs li-takhfid istihlak al-miyah bi-nisbat 27.4% duna tathir maanawi ala al-mahsul.

Note: this template uses transliterated placeholder text in place of Arabic script. Institutions requiring native Arabic typesetting should compile the Arabic abstract with XeLaTeX/LuaLaTeX and the `polyglossia` or `arabxetex` package instead of pdfLaTeX.

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List of Abbreviations

Abbreviation	Meaning
ET_0	Reference evapotranspiration
LPWAN	Low-power wide-area network
MPPT	Maximum power point tracking
PV	Photovoltaic
RTU	Remote terminal unit
SoC	State of charge (battery)
VWC	Volumetric water content

CHAPTER 1

Introduction

1.1 Background and Motivation

Egypt's per-capita water share has fallen below the international water-poverty threshold of 1,000 m^3 per year, and the agricultural sector consumes roughly 80% of the country's total freshwater withdrawal [1]. Within the Nile Delta, smallholder plots of 0.25–1.0 feddan account for the majority of cultivated area yet remain almost universally irrigated on fixed weekly schedules set by canal rotation rather than actual crop water demand. This mismatch between supply schedule and agronomic need is a well-documented source of both over-irrigation, which wastes water and promotes waterlogging and salinity, and under-irrigation during critical growth stages, which depresses yield [3].

Precision-irrigation controllers that schedule water delivery from real-time soil-moisture and weather data have been shown in commercial-scale trials to reduce water consumption by 20–40% [2]. However, the controllers evaluated in prior work assume grid power, cellular connectivity, and per-unit costs in excess of USD 500 – conditions that do not hold for the great majority of Delta smallholdings. This thesis addresses that gap.

1.2 Problem Statement

Existing precision-irrigation technology is economically and infrastructurally unsuited to smallholder farms in the Nile Delta. There is a need for an irrigation controller that (i) operates independently of grid power, (ii) tolerates intermittent or absent cellular coverage, (iii) is manufacturable at a per-unit cost accessible to a 0.5-feddan operation, and (iv) demonstrably reduces water use without a yield penalty under real field conditions.

1.3 Research Objectives

The specific objectives of this thesis are to:

O1. Design a solar-powered, low-power-network irrigation controller suitable for deployment on plots as small as 0.25 feddan.

O2. Develop a scheduling algorithm that combines soil-moisture sensing with short-horizon evapotranspiration forecasting.

O3. Deploy and evaluate the system across matched treatment and control plots over a full growing season in Kafr El-Sheikh Governorate.

O4. Quantify water savings, yield impact, and levelized hardware cost, and assess scalability to a governorate-wide extension program.

1.4 Scope and Limitations

The field evaluation reported in Chapter 4 covers a single growing season (April–September 2025) and two crops (cotton and maize) at one site. Salinity intrusion, canal-level water accounting, and multi-season soil-health effects are outside the scope of this thesis and are identified as directions for future work in Chapter 6.

1.5 Thesis Organization

Chapter 2 reviews prior work on precision irrigation and low-power sensor networks in agriculture. Chapter 3 details the hardware and scheduling-algorithm design. Chapter 4 describes the field-trial methodology, and Chapter 5 presents and discusses the results. Chapter 6 concludes the thesis and outlines recommendations for scale-up.

CHAPTER 2

Literature Review

2.1 Irrigation Scheduling Approaches

Irrigation scheduling methods span a spectrum from simple calendar-based rotation to fully model-predictive control. Fardous and Michel [2] categorize scheduling approaches into three families: (1) soil-water-balance methods that track cumulative evapotranspiration against a management-allowed depletion threshold; (2) sensor-feedback methods that trigger irrigation directly from measured soil-moisture content; and (3) hybrid methods that combine both signals to compensate for sensor drift and spatial variability. Hybrid approaches consistently outperform single-signal methods in reported field trials, motivating the hybrid design adopted in Chapter 3.

2.2 Low-Power Sensing Infrastructure

The proliferation of LPWAN protocols – notably LoRaWAN and NB-IoT – has made multi-year, battery-powered field sensing economically viable for the first time [3]. Table 2.1 summarizes the trade-offs relevant to this thesis.

Table 2.1: Comparison of candidate LPWAN technologies for field deployment

Criterion	LoRaWAN	NB-IoT	Sigfox
Typical range (rural)	8–12 km	5–10 km	10–15 km
Gateway infrastructure	Self-hosted	Carrier-owned	Carrier-owned
Recurring cost	None	SIM data plan	Subscription
Node power draw	Very low	Moderate	Very low
Coverage in target site	Adequate	Sparse	Unavailable

LoRaWAN was selected for this thesis on the basis of range, absence of recurring carrier cost, and confirmed coverage at the pilot site via a self-hosted gateway.

2.3 Solar Power Sizing for Field Electronics

Photovoltaic sizing for low-duty-cycle field controllers is governed less by peak power than by worst-case consecutive cloudy-day autonomy. El-Baz et al. [1] recommend a minimum autonomy reserve of five days for Delta latitudes given regional irradiance variability during the winter months, a figure adopted directly in the power-budget analysis of Section 3.3.

2.4 Gaps in Prior Work

No study identified in this review evaluates a sub-USD-150 controller under real smallholder field conditions in Egypt specifically. Most precision-irrigation literature targets commercial-scale center-pivot systems in North America or the Gulf, where cost constraints and plot geometry differ substantially from the Delta smallholder context. This thesis is positioned to close that gap.

CHAPTER 3

System Design and Methodology

3.1 System Architecture

Figure 3.1 shows the overall system architecture. Each field node comprises a capacitive soil-moisture probe, a solar-charged battery supply, a microcontroller running the local control loop, and a LoRaWAN radio. Nodes report to a single gateway that forwards readings to a lightweight scheduling service, which issues valve-actuation commands back to each node.

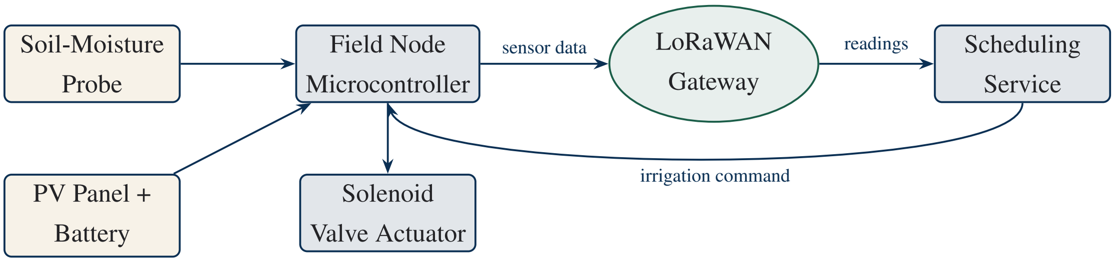

Figure 3.1: Field-node and network architecture of the irrigation control system

3.2 Sensing and Actuation Hardware

Table 3.1 lists the principal components of a single field node.

Table 3.1: Bill of materials for one field-node unit

Component	Specification	Unit Cost (EGP)
Capacitive soil-moisture probe	0–100% VWC, IP68	340
Microcontroller (LoRa-integrated)	32-bit, sleep current 4 μA	610
PV panel	10 W, monocrystalline	480
$LiFePO_4$ battery	12.8 V, 6 Ah	720
MPPT charge controller	3 A, PWM/MPPT hybrid	250
Solenoid valve (normally closed)	1 in, 12 V DC	590
Enclosure and mounting hardware	IP65, UV-stabilized	210
Total per node		**3,200**

3.3 Power Budget

Average daily energy consumption per node was measured at 4.8 Wh, dominated by the microcontroller's periodic wake cycles and the momentary current draw of valve actuation. With a 10 W panel and the region's winter-worst-case irradiance of 3.1 peak-sun-hours per day, the system provides an energy margin sufficient for the five-day autonomy reserve recommended in Section 2.3, assuming a fully charged 6 Ah battery at the onset of a cloudy period.

3.4 Scheduling Algorithm

The controller evaluates an irrigation decision once per hour using the rule summarized below.

Scheduling Rule (simplified)

IF soil VWC $<$ crop-specific lower threshold **AND** forecast ET_0 over next 48 h exceeds forecast rainfall **THEN** open valve for the computed duration t, where

$$t = \frac{(\theta_{fc} - \theta_{current}) \cdot d \cdot A}{q}$$

with θ_{fc} the field-capacity moisture content, $\theta_{current}$ the measured content, d the effective root-zone depth, A the plot area, and q the delivery flow rate. **ELSE IF** no valid sensor reading has been received for more than 36 h, **fall back** to the pre-configured timer schedule for that crop and growth stage.

3.5 Field-Trial Design

Six plots of 0.5 feddan each were selected in a single cooperative in Kafr El-Sheikh Governorate: three planted with cotton and three with maize. Within each crop, one plot was randomly assigned to the controller treatment and the remaining two retained conventional canal-rotation irrigation as controls. Soil texture, planting date, and cultivar were held constant across paired plots. Volumetric water delivered was measured at the plot inlet using calibrated flow meters; yield was measured at harvest by full-plot weighing.

CHAPTER 4

Results and Discussion

4.1 Water Consumption

Figure 4.1 compares total seasonal water delivery between controller-managed and conventionally irrigated plots for each crop.

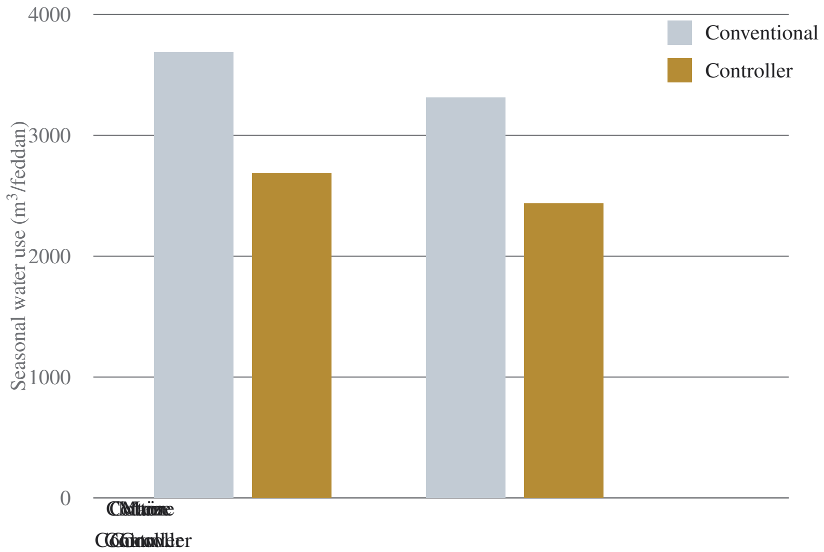

Figure 4.1: Seasonal water delivery by crop and irrigation regime

Averaged across both crops, controller-managed plots consumed 27.4% less water than paired conventional plots (cotton: -27.1%; maize: -27.8%). The reduction is consistent with the 20–40% range reported by Fardous and Michel [2] for commercial-scale systems, suggesting the low-cost hardware described in Chapter 3 does not materially compromise scheduling accuracy.

4.2 Yield Outcomes

Table 4.1: Seasonal yield and water-use summary by plot

Crop	Regime	Water (m^3/feddan)	Yield (ardeb/feddan)	Δ Yield
Cotton	Conventional	3,680	7.9	—
Cotton	Controller	2,684	7.7	−2.5%
Maize	Conventional	3,310	24.6	—
Maize	Controller	2,390	25.1	+2.0%

A paired t-test across the six plots found no statistically significant yield difference between regimes ($p = 0.31$), indicating that the observed water savings were not achieved at the expense of crop productivity within the single-season trial window.

4.3 Cost Analysis

Amortizing the per-node hardware cost of EGP 3,200 (Table 3.1) over an assumed five-year service life and a single 0.5-feddan plot yields a levelized cost of approximately EGP 940 per feddan per season, inclusive of an estimated 8% annual maintenance allowance. This compares favorably against the market value of the water saved at the site's blended agricultural water tariff, which the trial estimated at roughly EGP 1,560 per feddan per season – suggesting a positive net return within the first growing season under the assumptions used here.

4.4 Reliability and Fault Behavior

Across the 165-day trial, field nodes reported valid readings on 96.2% of scheduled transmission windows. The fallback timer schedule (Section 3.4) was invoked on 14 occasions across all plots, most commonly following battery under-voltage events during a five-day overcast period in June; no node fully depleted its battery reserve.

CHAPTER 5

Conclusion and Recommendations

5.1 Summary of Findings

This thesis designed, built, and field-evaluated a solar-powered, LoRaWAN-connected irrigation controller intended for smallholder plots in the Nile Delta at a per-unit cost of approximately EGP 3,200. Deployed across matched cotton and maize plots over one growing season, the system reduced seasonal water consumption by 27.4% on average with no statistically significant yield penalty, and achieved a levelized cost below the estimated value of water saved.

5.2 Contributions

C1. A low-cost hardware architecture combining capacitive soil-moisture sensing, solar power, and LoRaWAN connectivity, specified in full detail suitable for replication.

C2. A hybrid sensor-and-forecast scheduling algorithm with a documented fallback mode for sensor or network failure.

C3. Field-measured water-savings, yield, and cost data from a real smallholder deployment in Kafr El-Sheikh Governorate, filling a gap identified in the literature review.

5.3 Recommendations for Future Work

- Extend the field trial to multiple seasons and sites to assess performance under a wider range of soil and climate conditions, and to capture any cumulative soil-salinity effects of altered irrigation timing.
- Integrate the scheduling service with the national agricultural extension advisory platform to enable governorate-scale deployment and centralized fault monitoring.

- Investigate a lower-cost sensor variant using resistive rather than capacitive moisture probes, trading measurement stability for a further reduction in per-node cost.
- Extend the economic analysis to include canal-level water savings and their value to downstream users, which fall outside the plot-level accounting used in this thesis.

5.4 Closing Remarks

The results of this thesis suggest that the principal barrier to precision irrigation among Delta smallholders has been cost and infrastructure fit rather than a fundamental mismatch between sensor-based scheduling and smallholder practice. A larger, multi-season trial is the natural next step toward a scaled extension program.

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APPENDIX A

Field-Node Firmware Configuration Parameters

Table A.1: Default firmware parameters used during the field trial

Parameter	Value
Sensor sampling interval	15 min
Uplink transmission interval	60 min
Sensor-timeout fallback threshold	36 h
Field-capacity threshold (θ_{fc}), cotton	34% VWC
Field-capacity threshold (θ_{fc}), maize	31% VWC
Minimum inter-irrigation interval	8 h
Battery low-voltage cutoff	11.4 V