Adaptive Irrigation Scheduling from Low-Cost Soil Moisture Sensor Networks

by

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Abstract

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Smallholder irrigation in water-scarce regions is frequently scheduled by fixed calendar rather than actual soil moisture, because commercial soil moisture sensor networks are too expensive to deploy at the density a scheduling decision needs. This thesis develops a low-cost capacitive soil moisture sensor network, built from off-the-shelf components at roughly a tenth of the cost of commercial equivalents, together with a scheduling algorithm that tolerates the sensor drift and noise such low-cost hardware introduces.

The sensor network was deployed across a nine-hectare deciduous fruit orchard alongside commercial capacitance probes for calibration, and the scheduling algorithm was evaluated over two irrigation seasons against both the grower's existing calendar-based schedule and a schedule driven by the commercial probes alone.

The low-cost network, combined with the drift-tolerant scheduling algorithm, reduced irrigation water use by 22% relative to the calendar schedule while maintaining yield within the season-to-season variation of the unirrigated control blocks, and matched the commercial-probe schedule's water use to within 4%, at roughly one-tenth of the sensor hardware cost.

Acknowledgements

I would like to thank my supervisors for their guidance throughout this project, the orchard management team who allowed a season of sensor prototypes into their irrigation blocks, and the Department of Agricultural Engineering's workshop staff for their help building three generations of sensor enclosures.

Dedication

For my grandmother, who irrigated by hand and by instinct, and never once needed a sensor to know when the soil was thirsty.

Table of contents

Acknowledgements **iii**

Dedication **iv**

List of figures **vi**

List of tables **vii**

List of symbols **viii**

1 Introduction **1**
1.1 Contributions 1

2 Literature Review **2**
2.1 Soil Moisture Sensing Technologies 2
2.2 Irrigation Scheduling Approaches 2
2.3 Gap Addressed by This Thesis 2

3 Drift-Tolerant Scheduling **3**
3.1 Sensor Drift Characterisation 3
3.2 Scheduling Decision 3
3.3 Noise Sensitivity 4

4 Field Evaluation **5**
4.1 Site and Deployment 5
4.2 Results 5
4.3 Cost 6

5 Conclusion **7**
5.1 Limitations and Further Work 7

A Sensor Calibration Procedure **8**

List of references **9**

List of figures

List of tables

3.1 Spurious irrigation trigger rate under measured sensor noise, five-sensor blocks. 4

4.1 Seasonal irrigation water use by scheduling policy, nine-hectare orchard, two-season average. 5

List of symbols

Constants

θ_{fc}	Soil moisture at field capacity, $0.32\,\text{m}^3\cdot\text{m}^{-3}$	

Variables

θ	Volumetric soil moisture content	$[\,\text{m}^3/\text{m}^3\,]$
θ_{wp}	Soil moisture at wilting point	$[\,\text{m}^3/\text{m}^3\,]$
$\hat{\theta}$	Drift-corrected sensor moisture estimate	$[\,\text{m}^3/\text{m}^3\,]$
D	Applied irrigation depth	$[\,\text{mm}\,]$
T	Reference evapotranspiration	$[\,\text{mm/day}\,]$

Subscripts

i	Sensor node index
k	Irrigation event index

Abbreviations

SMS	Soil moisture sensor
ETo	Reference evapotranspiration

Chapter 1

Introduction

Precision irrigation scheduling — watering according to measured soil moisture rather than a fixed calendar — has been shown to reduce water use substantially in commercial orchards (Smith and Baillie, 2019), but the capacitance and TDR (time-domain reflectometry) probes typically used are expensive enough that most smallholder and mid-sized growers cannot deploy them at the density a per-block scheduling decision requires.

This thesis develops a low-cost soil moisture sensor network, built from off-the-shelf capacitive sensors and microcontrollers at roughly a tenth of the cost of commercial probes, and a scheduling algorithm designed to tolerate the drift, noise and cross-sensor calibration variation that low-cost hardware introduces.

1.1 Contributions

- A drift-correction procedure that recalibrates each low-cost sensor in the field against periodic reference readings, described in Chapter 3.
- A field evaluation across two irrigation seasons in a nine-hectare deciduous fruit orchard, comparing the low-cost network against both a calendar schedule and a commercial-probe schedule, in Chapter 4.

Chapter 2

Literature Review

2.1 Soil Moisture Sensing Technologies

Time-domain reflectometry and commercial capacitance probes offer high accuracy and low drift, but at a per-node cost that limits deployment density on a typical grower's budget (Smith and Baillie, 2019). Low-cost capacitive sensors, built from generic soil-moisture modules and a microcontroller, cost an order of magnitude less but exhibit substantially more sensor-to-sensor variation and drift over a growing season.

2.2 Irrigation Scheduling Approaches

Calendar-based scheduling — irrigating on a fixed interval regardless of actual soil state — remains the dominant practice among smallholder growers, largely because it requires no sensing infrastructure at all. Moisture-based scheduling, by contrast, requires sensor readings accurate and dense enough to distinguish a genuinely dry block from one that merely reads dry due to sensor drift (Jones and Vaughan, 2021). This is the specific gap this thesis addresses: making moisture-based scheduling viable with sensors too noisy for direct threshold-based control.

2.3 Gap Addressed by This Thesis

No prior work evaluates a drift-tolerant scheduling algorithm built specifically around low-cost sensor characteristics, in a real commercial orchard, against both the calendar baseline growers actually use and a commercial-probe upper bound. Chapter 4 provides that three-way comparison.

Chapter 3

Drift-Tolerant Scheduling

3.1 Sensor Drift Characterisation

Low-cost capacitive sensors drift over a growing season due to temperature sensitivity, electrode corrosion, and soil-specific calibration error. Rather than relying on the sensor's raw reading θ_i directly, the scheduling algorithm maintains a drift-corrected estimate $\hat{\theta}_i$, updated whenever a reference reading (from a hand-held capacitance probe, taken weekly) is available:

$$\hat{\theta}_i(t) = \theta_i(t) + \left(\theta_i^{\text{ref}} - \theta_i(t_{\text{ref}})\right) \tag{3.1}$$

where θ_i^{ref} is the reference reading and t_{ref} the time it was taken. Between reference readings, the correction term is held constant, which is why the algorithm needs to tolerate drift *within* a correction interval, not just across the season.

3.2 Scheduling Decision

Irrigation is triggered for a block when the median drift-corrected estimate across that block's sensor nodes falls below a threshold set relative to field capacity and wilting point:

$$\text{median}_i\{\hat{\theta}_i\} < \theta_{\text{wp}} + 0.4\,(\theta_{\text{fc}} - \theta_{\text{wp}}) \tag{3.2}$$

Using the block median rather than any single sensor's reading is what makes the policy tolerant of individual sensor noise: Section 3.3 shows that a single-sensor threshold policy triggers spurious irrigation events at more than triple the rate of the median-based policy under the noise levels measured on the low-cost hardware.

3.3 Noise Sensitivity

Table 3.1: Spurious irrigation trigger rate under measured sensor noise, five-sensor blocks.

Trigger policy	Spurious triggers / season
Single sensor, raw reading	14.2
Single sensor, drift-corrected	9.6
Block median, drift-corrected (this work)	3.1

Table 3.1 shows the drift correction alone reduces spurious triggers by a third, and combining it with block-median aggregation reduces them by a further two-thirds again, since a single sensor's transient noise spike rarely coincides with a matching spike across the whole block.

Chapter 4

Field Evaluation

4.1 Site and Deployment

The sensor network and scheduling policy were deployed across a nine-hectare deciduous fruit orchard over two irrigation seasons, alongside the grower's existing commercial capacitance probes used for calibration and as an upper-bound comparison. Three scheduling policies were compared on matched blocks: the grower's existing calendar schedule, a schedule driven directly by the commercial probes, and the low-cost network with the drift-tolerant policy of Chapter 3.

Table 4.1: Seasonal irrigation water use by scheduling policy, nine-hectare orchard, two-season average.

Policy	Water use (ML/ha)	Yield (t/ha)
Calendar (grower baseline)	6.8	41.2
Commercial probes	5.2	41.6
Low-cost network (this work)	5.3	41.0

4.2 Results

Table 4.1 shows the low-cost network reduces water use by 22% relative to the calendar baseline, and matches the commercial-probe schedule's water use to within 4%, while yield across all three policies stays within the season-to-season variation observed on this orchard's un-irrigated control blocks (not shown).

4.3 Cost

The full nine-hectare deployment (45 sensor nodes) cost approximately one-tenth of an equivalent commercial capacitance-probe deployment at the same node density, which is the deployment density Section 3.3 of Chapter 3 identifies as necessary for the block-median policy's noise tolerance to hold.

Chapter 5

Conclusion

This thesis has shown that a low-cost soil moisture sensor network, combined with a drift-correction and block-median scheduling policy, can match a commercial-probe irrigation schedule's water savings to within 4%, at roughly one-tenth of the sensor hardware cost. The block-median aggregation in Chapter 3 is what makes this possible: it is specifically what tolerates the higher per-sensor noise of low-cost hardware, rather than requiring individually accurate sensors.

5.1 Limitations and Further Work

The evaluation in Chapter 4 covers one orchard, one crop, and two seasons; the weekly reference-reading interval used for drift correction was chosen for this deployment's logistics and may need to be shorter for sensors or soils with faster drift characteristics. A natural extension is to make the reference interval itself adaptive, triggered by the variance of a block's sensor readings rather than a fixed weekly schedule.

Appendix A

Sensor Calibration Procedure

This appendix would normally reproduce the full field calibration procedure against the reference capacitance probe, including the soil-specific calibration curves fitted for each of the orchard's three soil types. They are omitted from this starter template; a real thesis appendix would include the fitted curves and their R^2 values alongside the raw calibration dataset.

List of references

Jones, H.G. and Vaughan, R.A. (2021). Low-cost soil moisture sensing for smallholder irrigation scheduling. *Computers and Electronics in Agriculture*, vol. 184, p. 106088.

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