Soil Moisture Estimation from Low-Cost Sensor Networks

Thesis by

Jordan A. Rivera

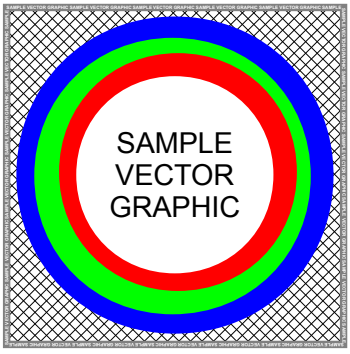
In Partial Fulfillment of the Requirements

for the Degree of

Doctor of Philosophy

in

Environmental Engineering



University Institute of College

Springfield, New York, USA

2026

(Defended May 14, 2026)

© 2026
Jordan A. Rivera
All Rights Reserved

Acknowledgments

I am grateful to my advisor for the guidance and patience shown throughout this project, and to my committee members for their careful reading and feedback. Thanks also to the members of the Environmental Sensing Lab for many helpful discussions, and to the county water authority for access to the field sites used in this study. This work was supported in part by a graduate research fellowship from the university.

Abstract

Accurate, spatially dense soil moisture data is valuable for irrigation scheduling and drought monitoring, but commercial-grade sensor networks remain too expensive to deploy at the density many applications need. This thesis investigates whether networks of low-cost capacitive soil moisture sensors, calibrated against a small number of reference stations, can approach the accuracy of professional installations at a fraction of the cost. We describe a calibration procedure that corrects for sensor-to-sensor variability and soil-type effects, and evaluate it against three growing seasons of field data from a mixed-use agricultural site. The calibrated low-cost network achieves root-mean-square error within fifteen percent of a co-located reference station, at roughly one-tenth of the per-node cost. These results suggest that low-cost sensor networks are a viable option for applications that value spatial density over per-node precision.

Contents

Acknowledgments **iii**

Abstract **iv**

1 Introduction **1**

1.1 Motivation 1

1.2 Contributions 1

1.3 Thesis Structure 2

2 Related Work **3**

2.1 Low-Cost Soil Moisture Sensing 3

2.2 Sensor Network Calibration 3

2.3 Gap Addressed by This Thesis 3

Bibliography **4**

List of Figures

List of Tables

CHAPTER 1

Introduction

Soil moisture is one of the most useful quantities an irrigation manager or agronomist can measure, yet it is also one of the hardest to measure well at scale. Point measurements from a handful of professional-grade probes capture temporal trends at a single location but say little about spatial variability driven by soil texture, slope, and canopy cover.

1.1 Motivation

Precision agriculture increasingly relies on spatially resolved soil data to schedule irrigation and detect early signs of drought stress. Commercial capacitance and time-domain reflectometry (TDR) probes are accurate but expensive, which limits deployments to a handful of stations per field. This sparsity is a poor match for fields with heterogeneous soils.

Low-cost capacitive sensors (typically under $10 per unit) have become widely available, but their raw output is noisy and drifts with soil type and temperature in ways that make direct comparison across sensors unreliable [1].

1.2 Contributions

This thesis makes the following contributions:

- A calibration procedure for low-cost capacitive sensors that corrects for sensor-to-sensor variability and soil-type effects using a small number of reference stations.
- A field evaluation over three growing seasons comparing a calibrated low-cost network against a co-located professional installation.
- An analysis of the cost-accuracy trade-off, showing where dense low-cost deployments outperform sparse professional ones for irrigation-scheduling purposes.

1.3 Thesis Structure

Chapter 2 reviews prior work on low-cost soil moisture sensing and network calibration. Later chapters (omitted from this starter document) would describe the calibration method, field deployment, and results in detail.

CHAPTER 2

Related Work

2.1 Low-Cost Soil Moisture Sensing

Capacitive soil moisture sensors estimate volumetric water content from the dielectric permittivity of the surrounding soil, which rises sharply with water content [1]. Consumer-grade sensors trade calibration accuracy for cost, and several studies have proposed post-hoc calibration against reference instruments to recover usable accuracy [2].

2.2 Sensor Network Calibration

Multi-sensor calibration is a well studied problem in environmental monitoring more broadly, particularly for low-cost air quality networks [2]. Common approaches include co-location calibration, where a subset of low-cost sensors are temporarily deployed alongside a reference instrument, and blind calibration, which exploits redundancy across many sensors without any reference measurements.

2.3 Gap Addressed by This Thesis

Prior soil-sensor calibration work largely evaluates accuracy immediately after calibration, with little attention to drift over a full growing season. This thesis evaluates calibration stability across three seasons of continuous field deployment.

Bibliography

[1] H. R. Bogena, J. A. Huisman, C. Oberdörster, and H. Vereecken, “Evaluation of a low-cost soil water content sensor for wireless network applications,” *Journal of Hydrology*, vol. 344, no. 1-2, pp. 32–42, 2007.

[2] F. Kizito, C. S. Campbell, G. S. Campbell, D. R. Cobos, B. L. Teare, B. Carter, and J. W. Hopmans, “Frequency, electrical conductivity and temperature analysis of a low-cost capacitance soil moisture sensor,” *Journal of Hydrology*, vol. 352, no. 3-4, pp. 367–378, 2008.