Tracking Soil Saturation in Earthen Embankments Using a Network of Wireless Conductivity Sensors

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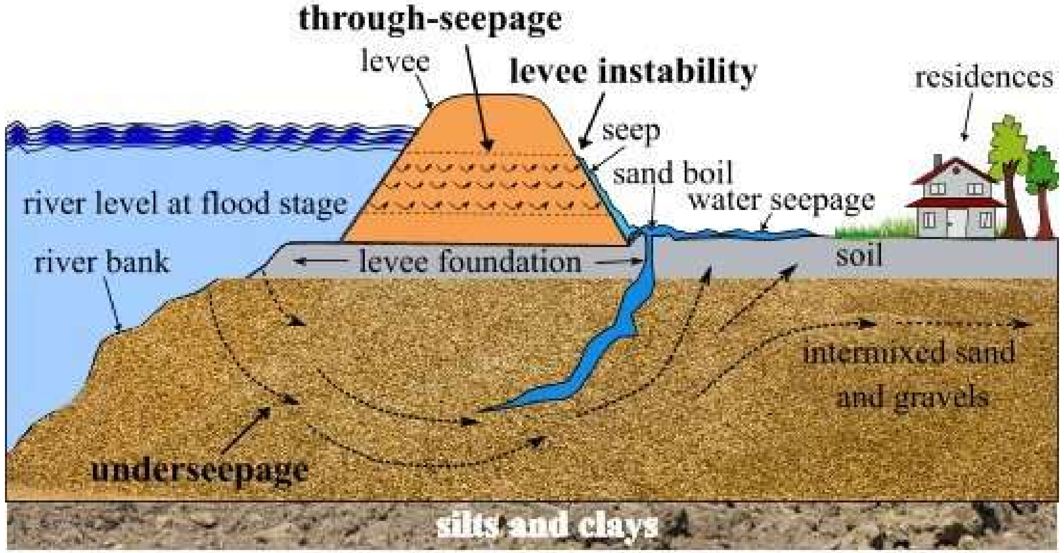
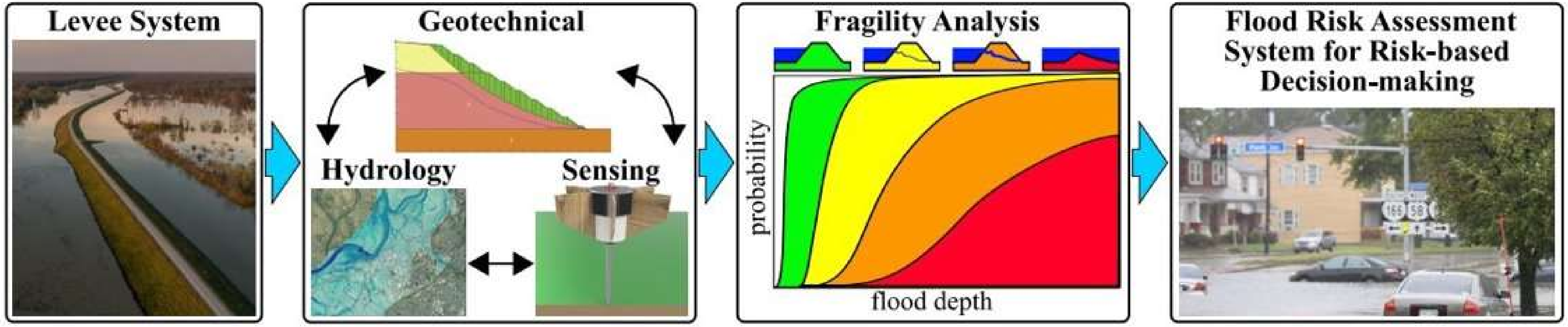
Outline

- ❑ Introduction
- ❑ Risk assessment
- ❑ Previous work
- ❑ Paper focus
- ❑ Data analysis
- ❑ Future work

Introduction

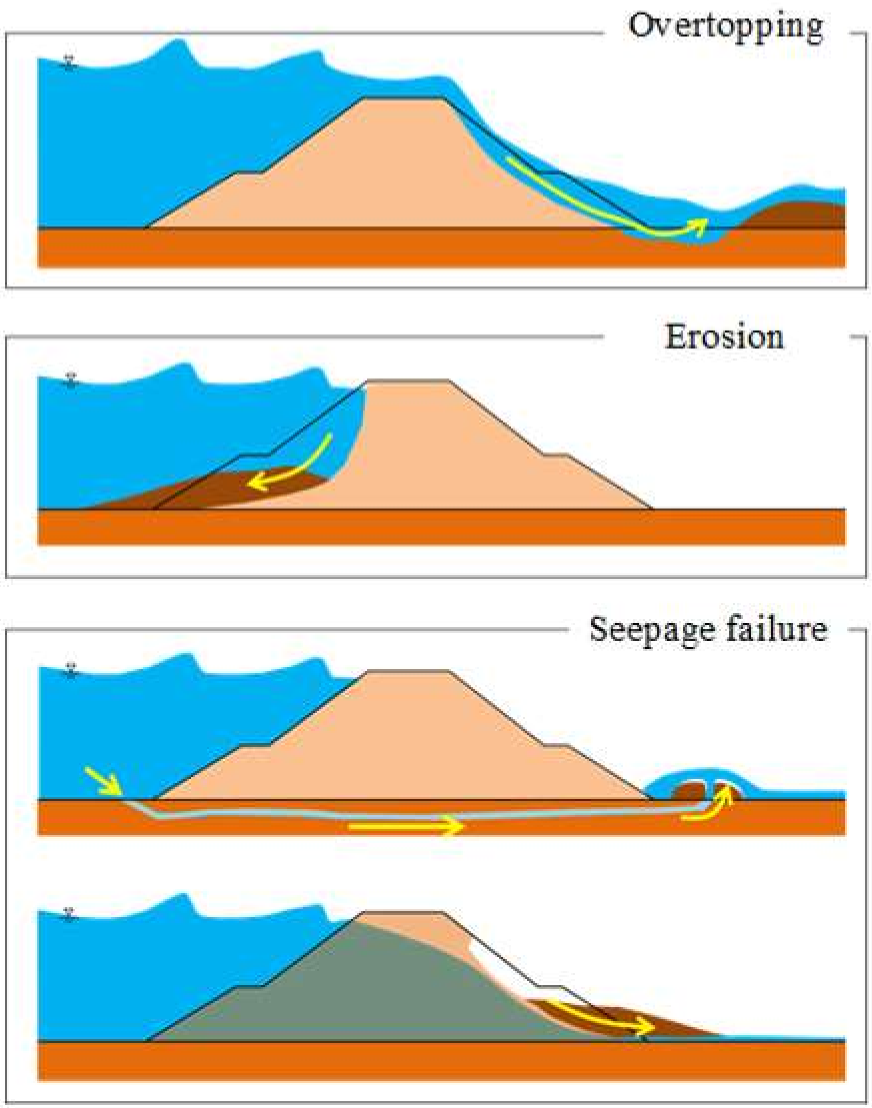
- Levees are human-made embankments built to prevent the overflow of water bodies (e.g. rivers).
- Critical in safeguarding communities and assets From flood damage.
- Typically made of compacted dirt
  - Erosion from moving water increases risk of breaching





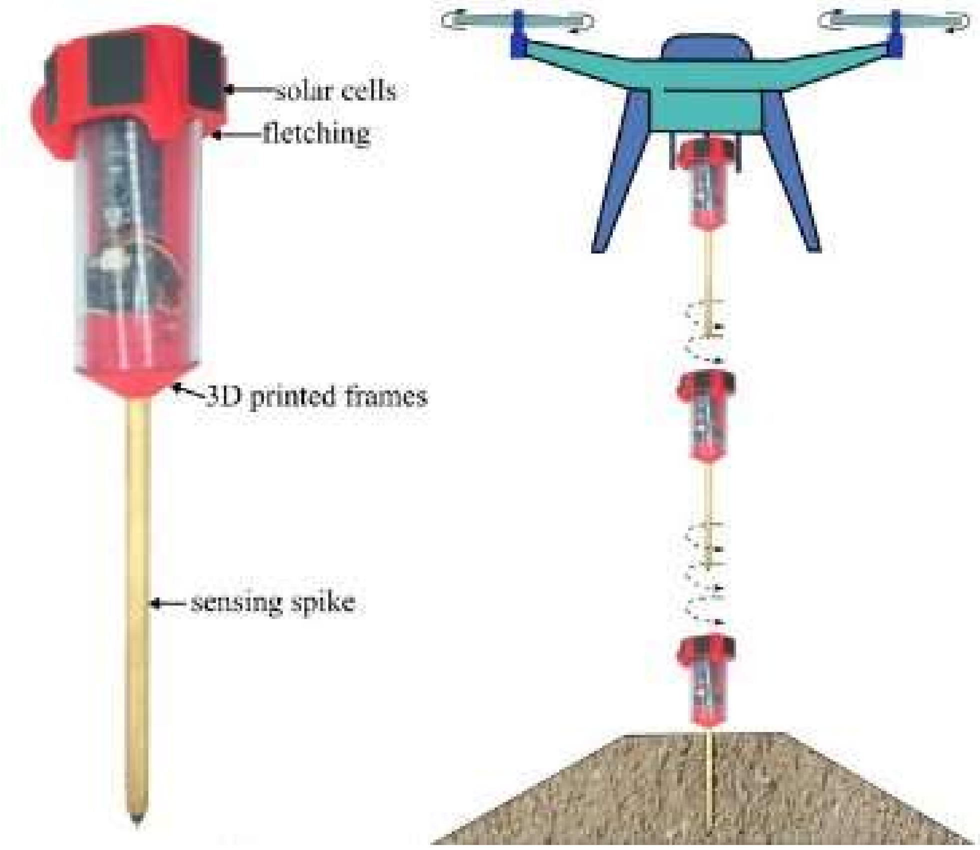
Risk Assessment of Levee Breach

- This work is part of a larger effort to develop a data-driven fragility framework for risk assessment of levee breach.
- This presentation will focus on the development of a network of wireless sensing spike packages for soil conductivity levels in levees.
- This work is being done in close collaboration with experts in data-driven assessment, geo-technical, and hydrology.



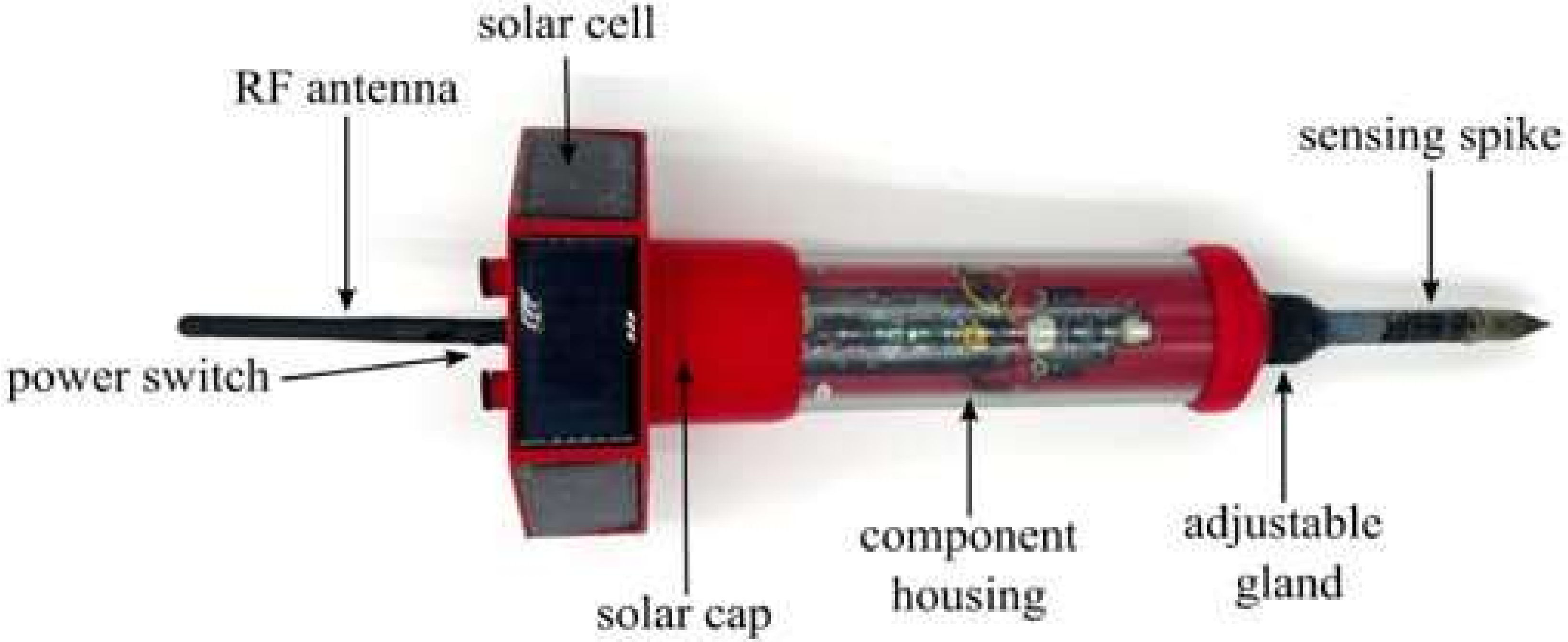
Conductivity-based Monitoring of a Levee

- Goal is to make UAV-deployable sensor systems.
- Currently working on sensor design (deployment comes later)



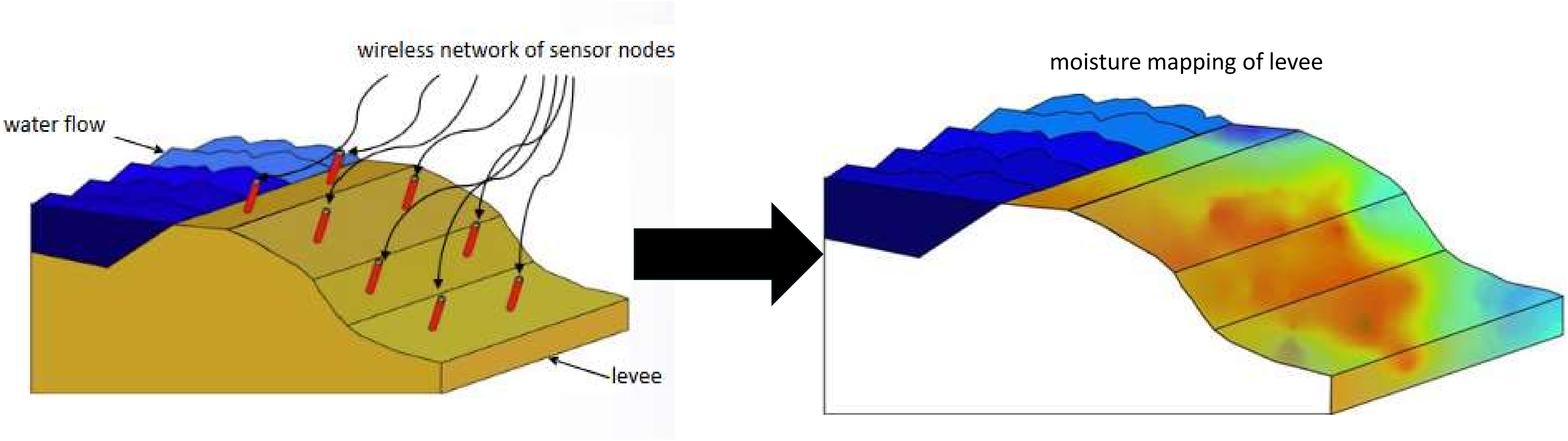
Open-Source SPECIES Project

GitHub Repository

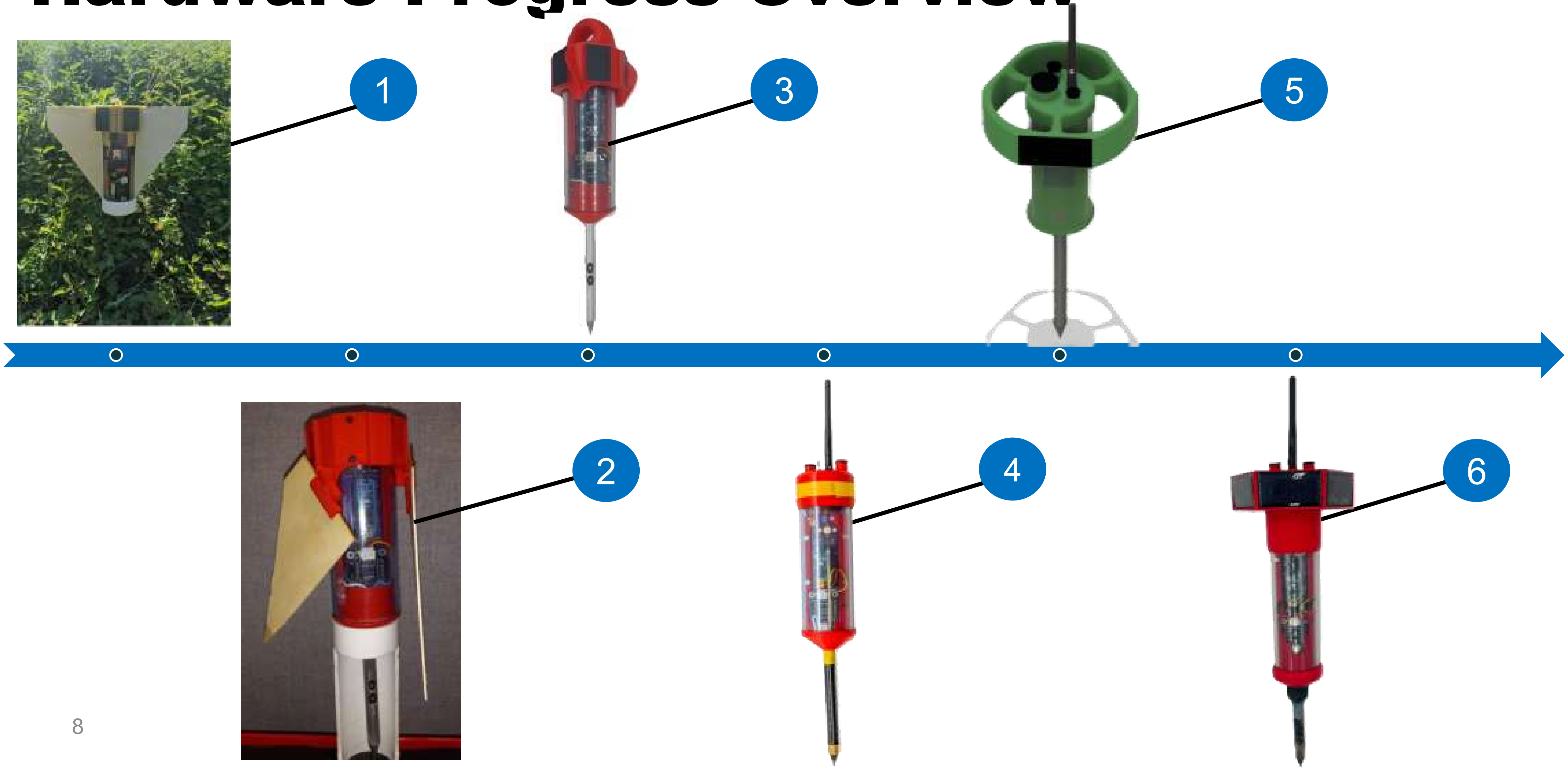


Monitoring using Wireless Sensor Network

- A wireless sensor network of sensor nodes is used to transmit data directly to a base station hub.

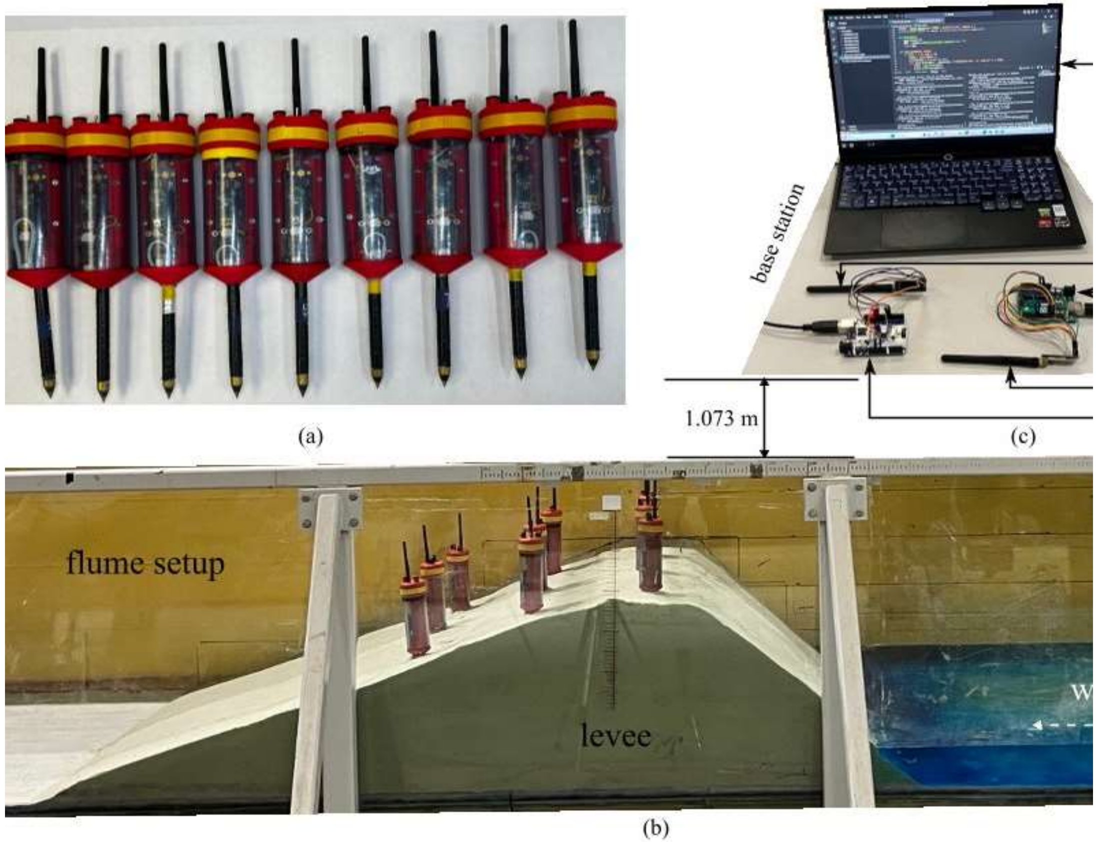


Hardware Progress Overview



Soil Saturation Experiment Setup

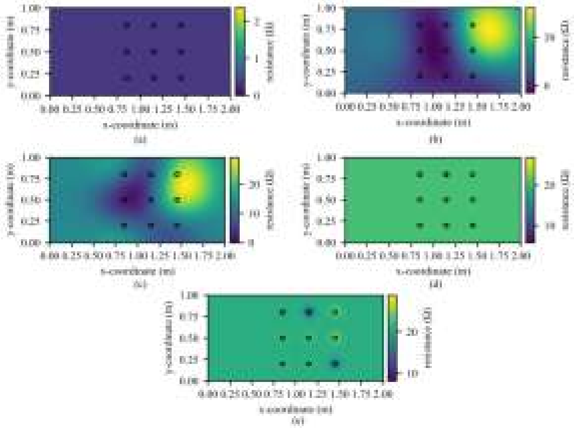
- Experimental validation of wireless soil saturation monitoring system utilizing a sand-filled levee model constructed within a controlled flume environment.

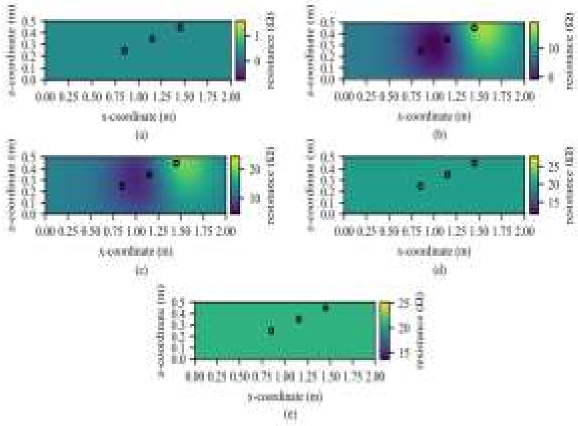


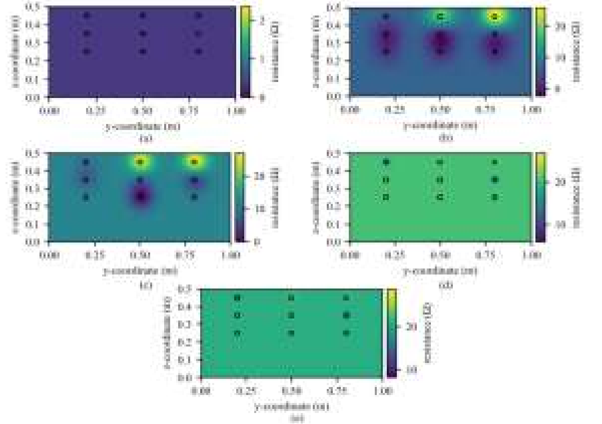
Soil Saturation Visualization

XY plane | XZ plane | YZ plane

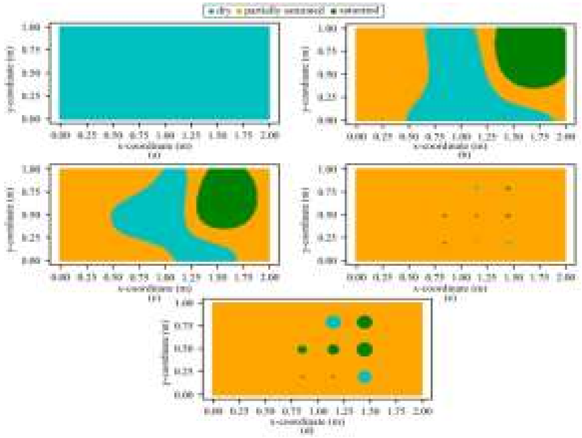
kriging

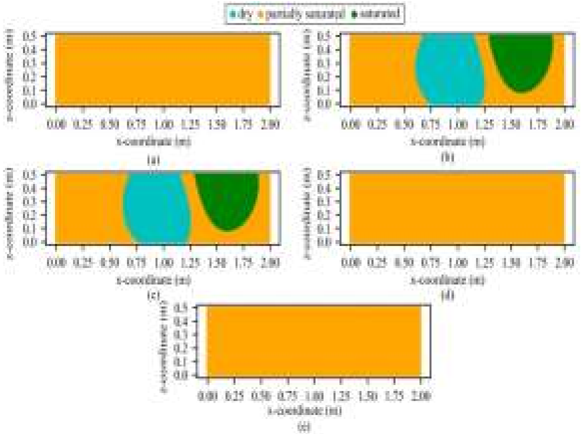


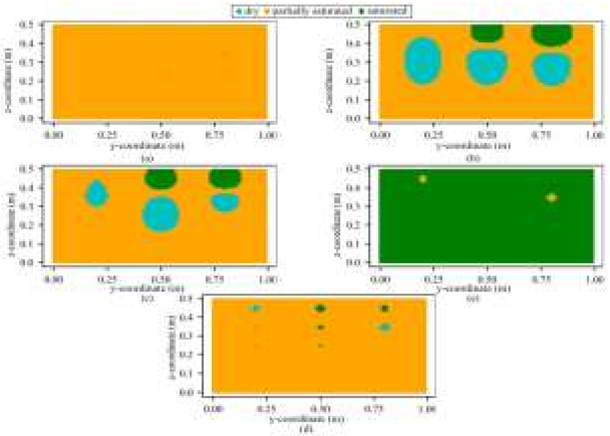




clustering



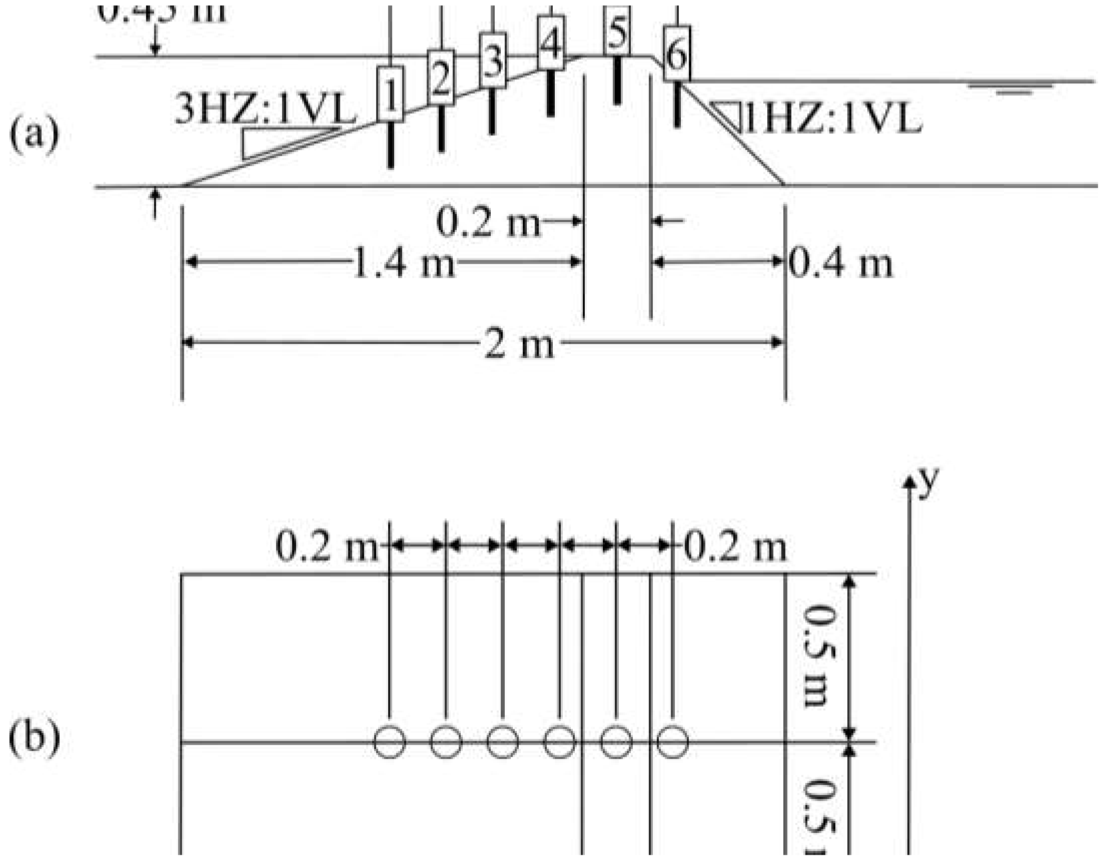




Case Studies #1

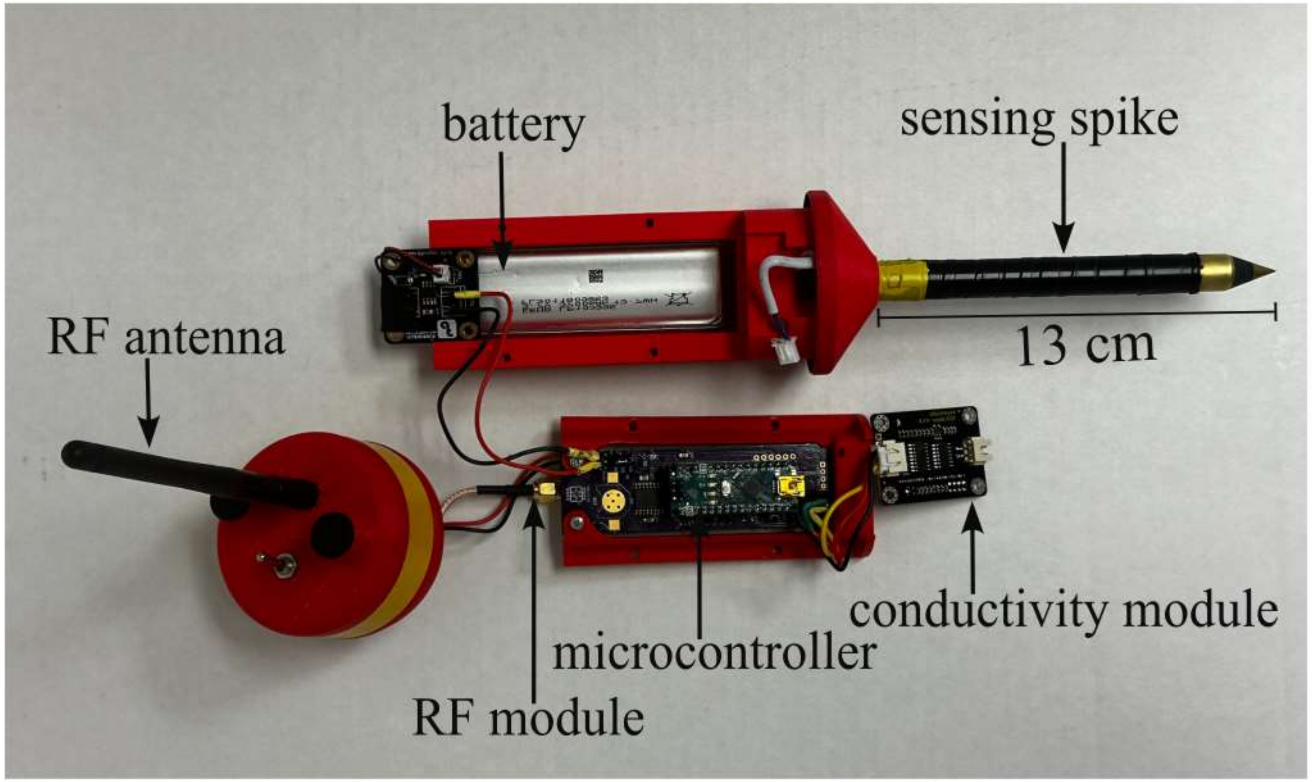
IDETC 2025 Paper Focus

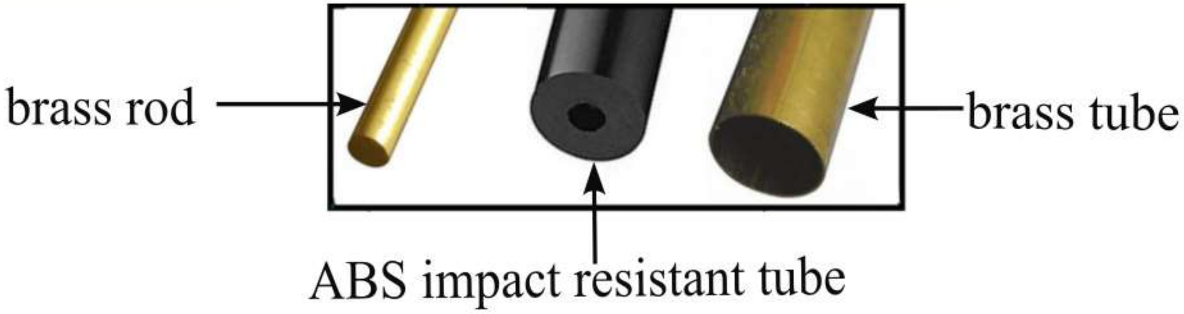
- This paper focuses on the long-term capability of the current wireless sensing spike package network.
- The long-term performance is important for continuous real-time in-situ monitoring in outdoor environments.



SPECIES Columbia V0.6.0

- Changes from Mississippi V0.1:
  - 3D printed PLA housing + clear PVC tube
  - Upgraded RF module (external antenna)
  - Total dissolved solids (TDS) for EC measurements
  - BME280 for internal environment readings



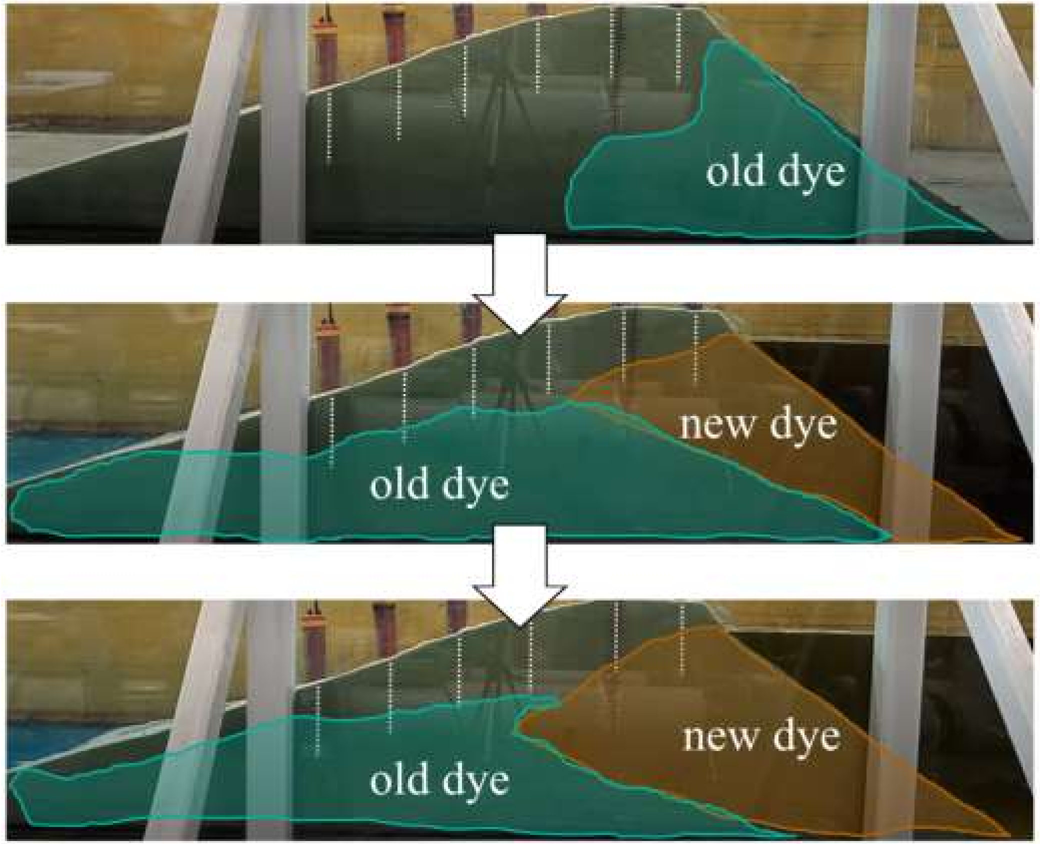


Experimental Setup

- 6 spikes in a straight line across a levee
- Controlled and monitored 144-hour test

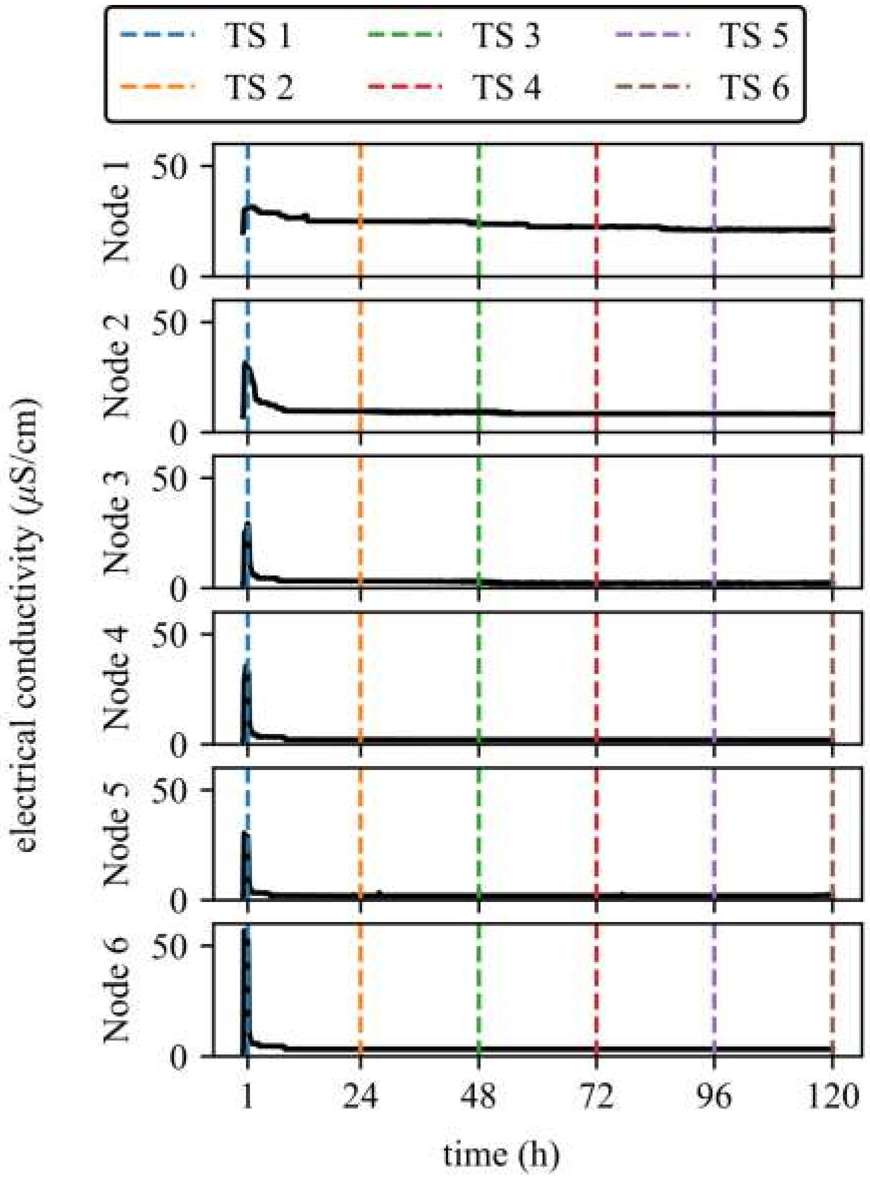
Levee Wetting

- **Visualizes Water Paths:** Dye traces reveal how water infiltrates and migrates through the levee over time, complementing sensor measurements.
- **Blue vs. Orange Dye:** Incoming orange dye pushes out remnants of blue dye from a prior test, clearly showing new infiltration fronts.

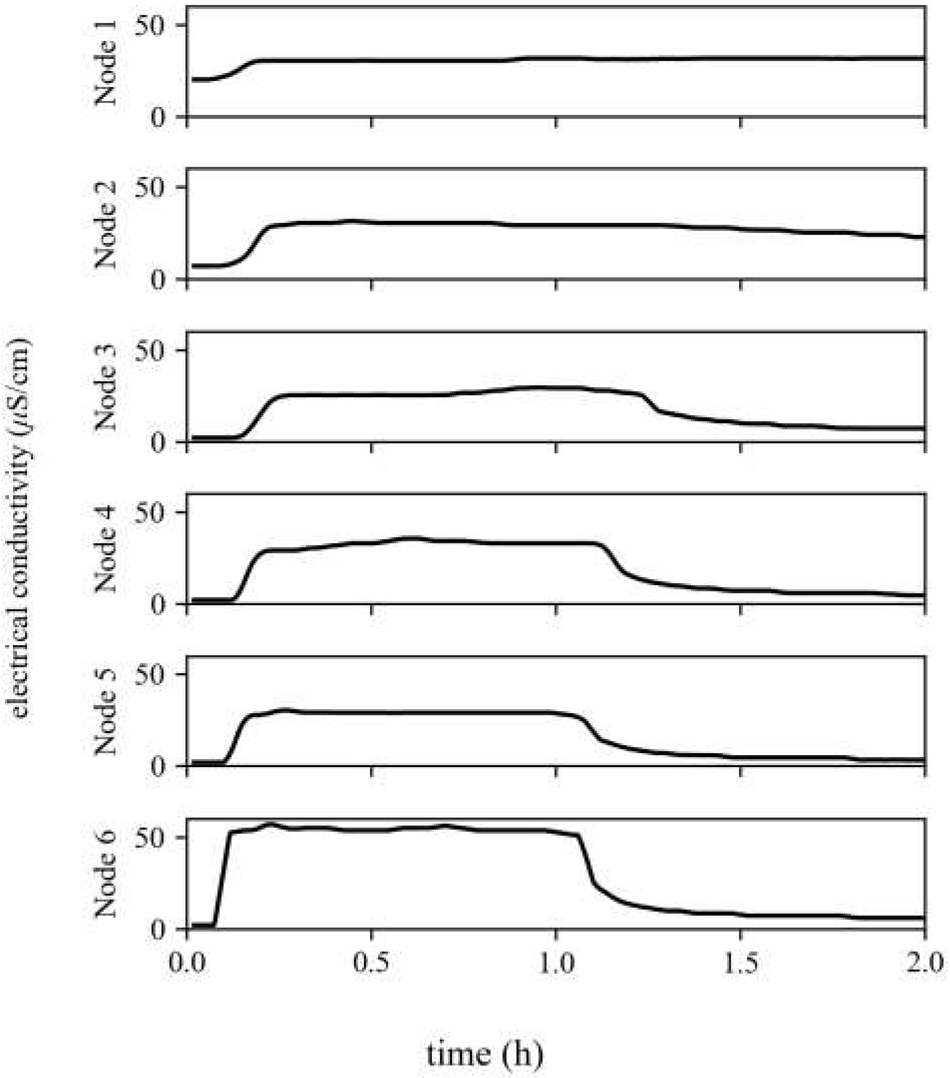


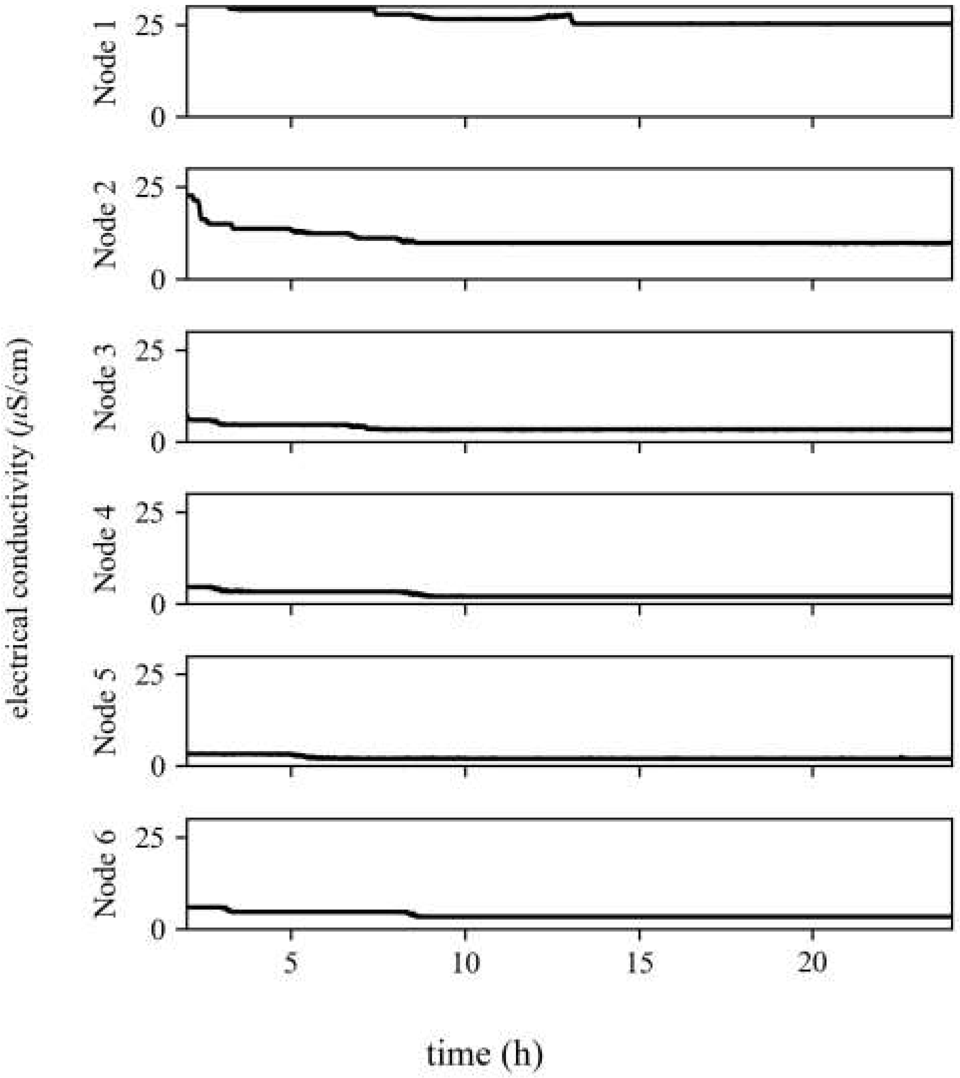
Experimental data

- **Individual Spike Trends:** Plots electrical conductivity over time for each sensing spike during the wetting-drying cycle.
- **Lower Spikes Retain Moisture:** Spikes 1 and 2, located near the base, record elevated electrical conductivity values for the longest duration, confirming water pooling at the bottom.
- **Faster Drying at Higher Locations:** Spikes 3-6, positioned higher on the embankment, show quicker decreases in conductivity as water drains downward.



Drying Cycle





Basis Splines

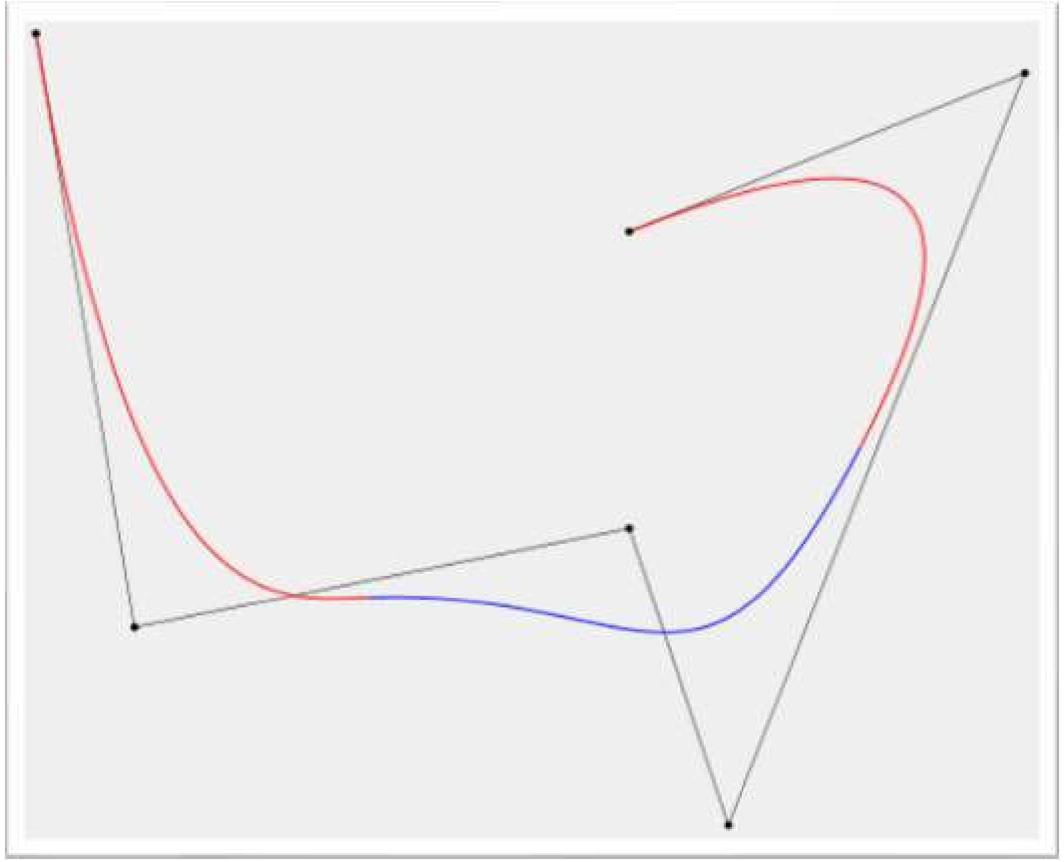
A B-Spine curve, $C(t)$ is given by

$$C(t) = \sum_{i=0} N_{i,k}(t) P_i$$

where $N_{i,k}$ are the basis functions of degree k, t is the parametric variable and P_i are the shape-defining control points.

B-splines are essentially a series of piece-wise polynomial functions used to fit non-linear models by dividing the dataset using the “knots”, t_i:

$$N_{i,0}(t) = \begin{cases} 1, t_i < t < t_{i+1} \\ 0, \text{otherwise} \end{cases}$$



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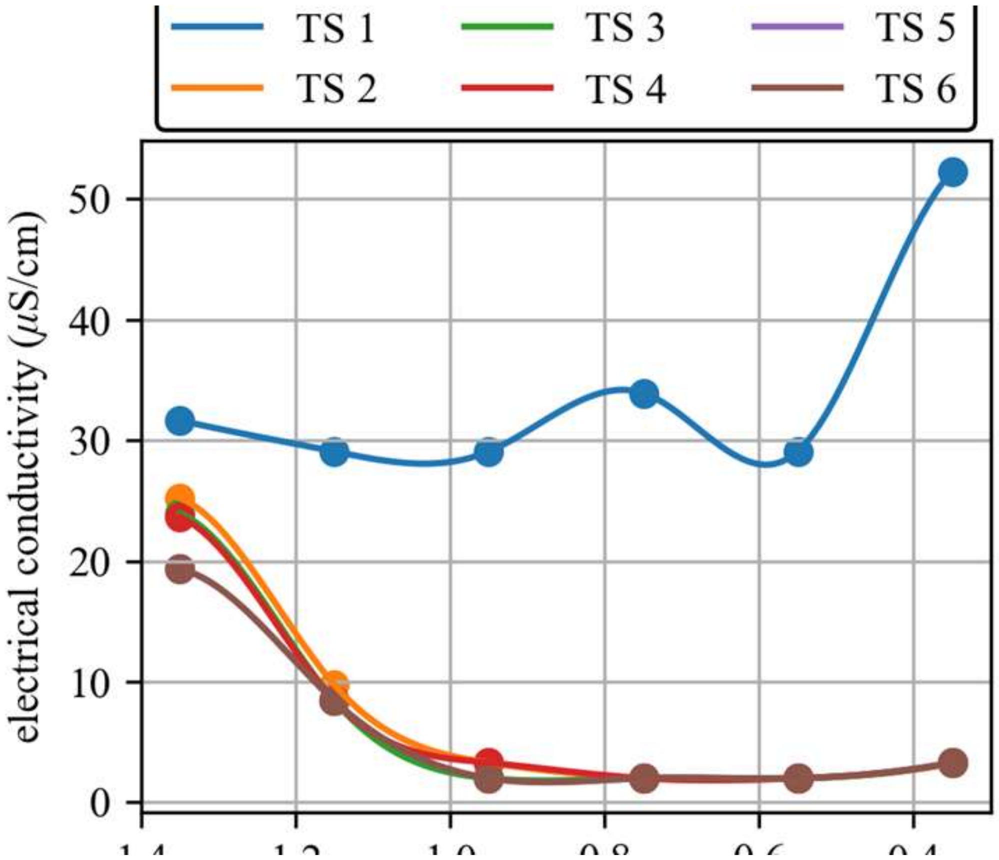
Experimental Data

- The conductivity starts high as the levee is saturated.
- Conductivity rapidly drops as the water leaves the levee.



Case Studies #2

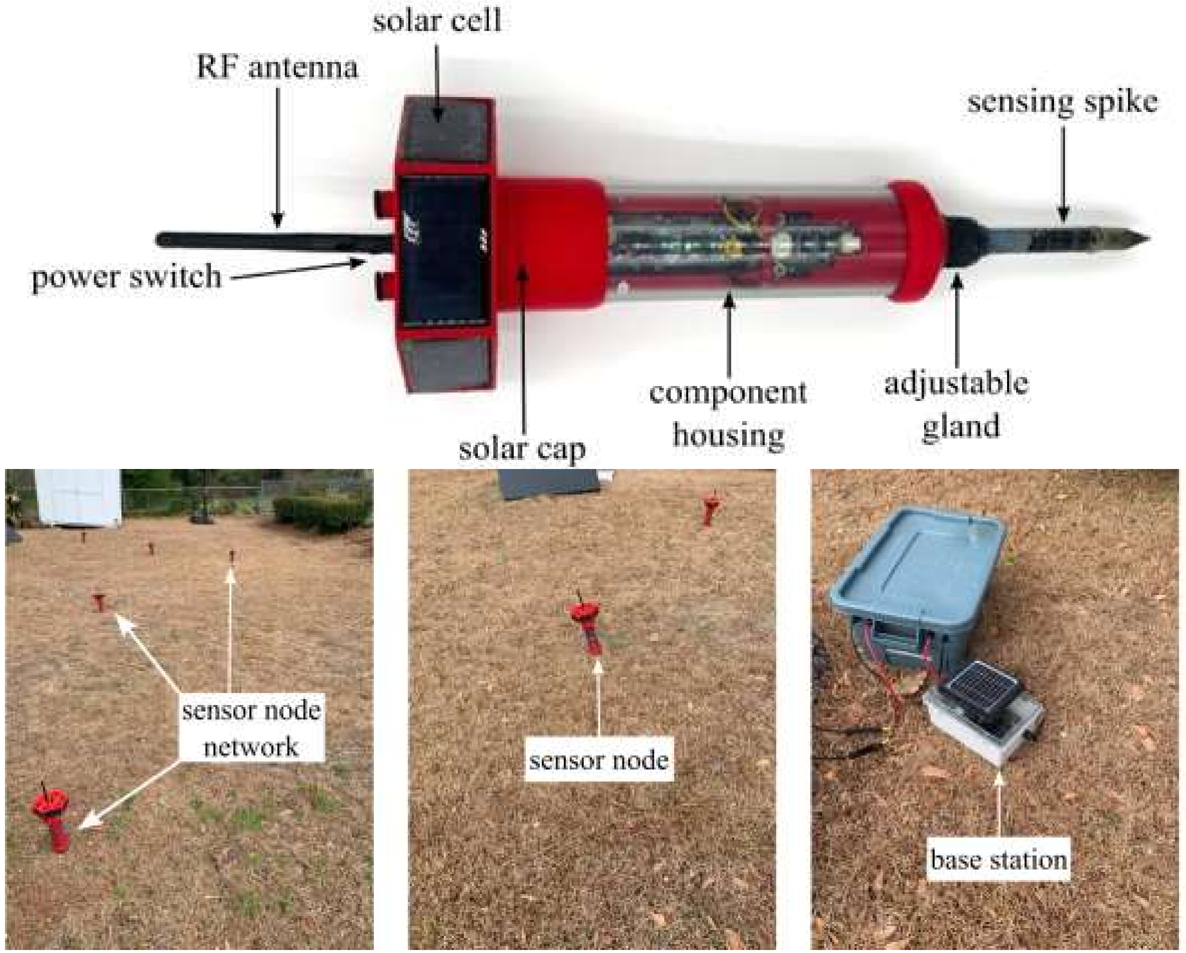
Wireless Sensor Network System Design and Field Deployment

Top Panel: Sensor Node Diagram
Shows a labeled close-up of a wireless sensor node highlighting key components include:

Panel (a): Field Deployment
Arrows indicate the formation of a sensor node network. Demonstrates real-world deployment in an outdoor environment.

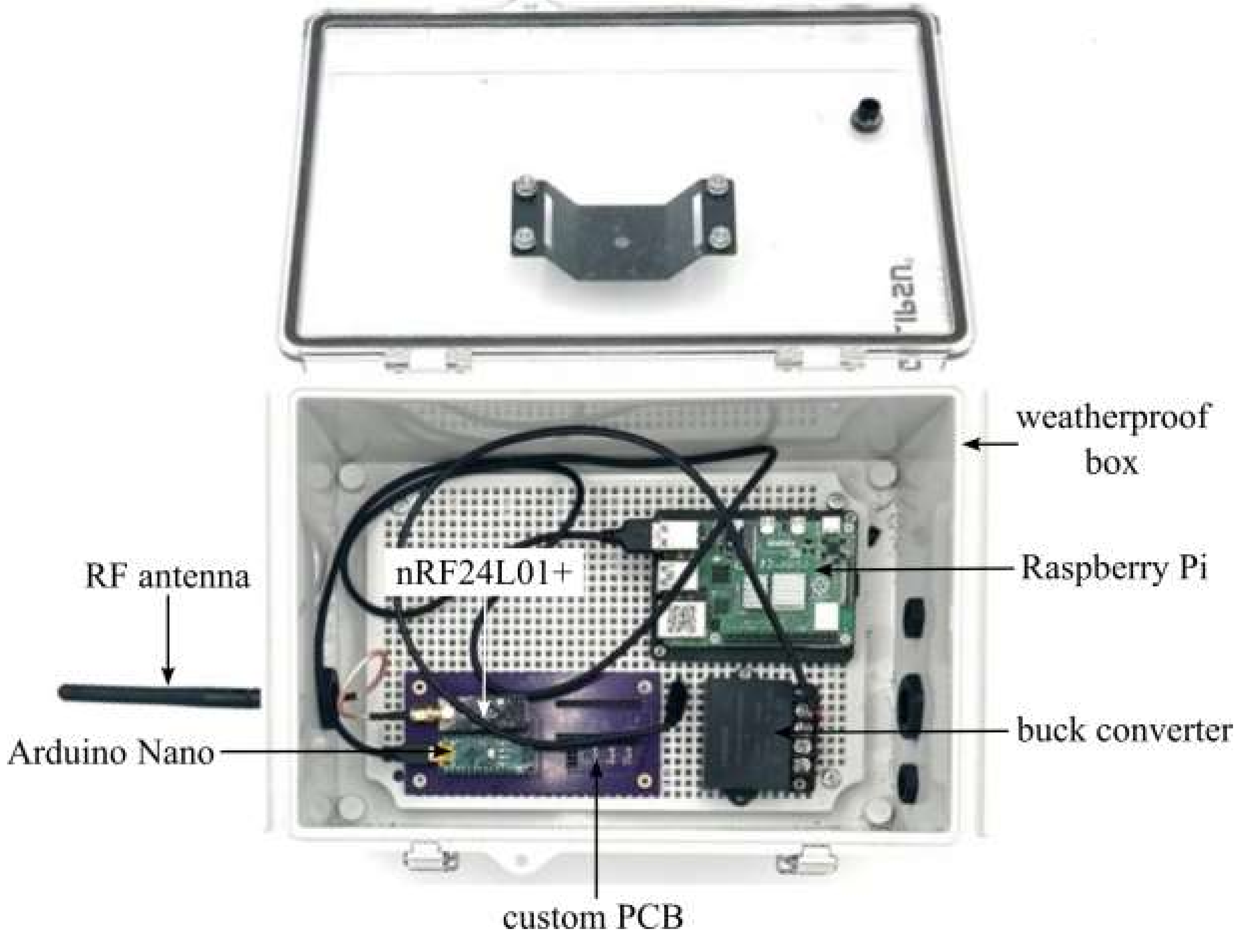
Panel (b): Single Sensor Node
Provides a close-up view of one sensor node embedded in the soil.

Panel (c): Base Station Setup
Shows the **base station** that receives data from sensor nodes.



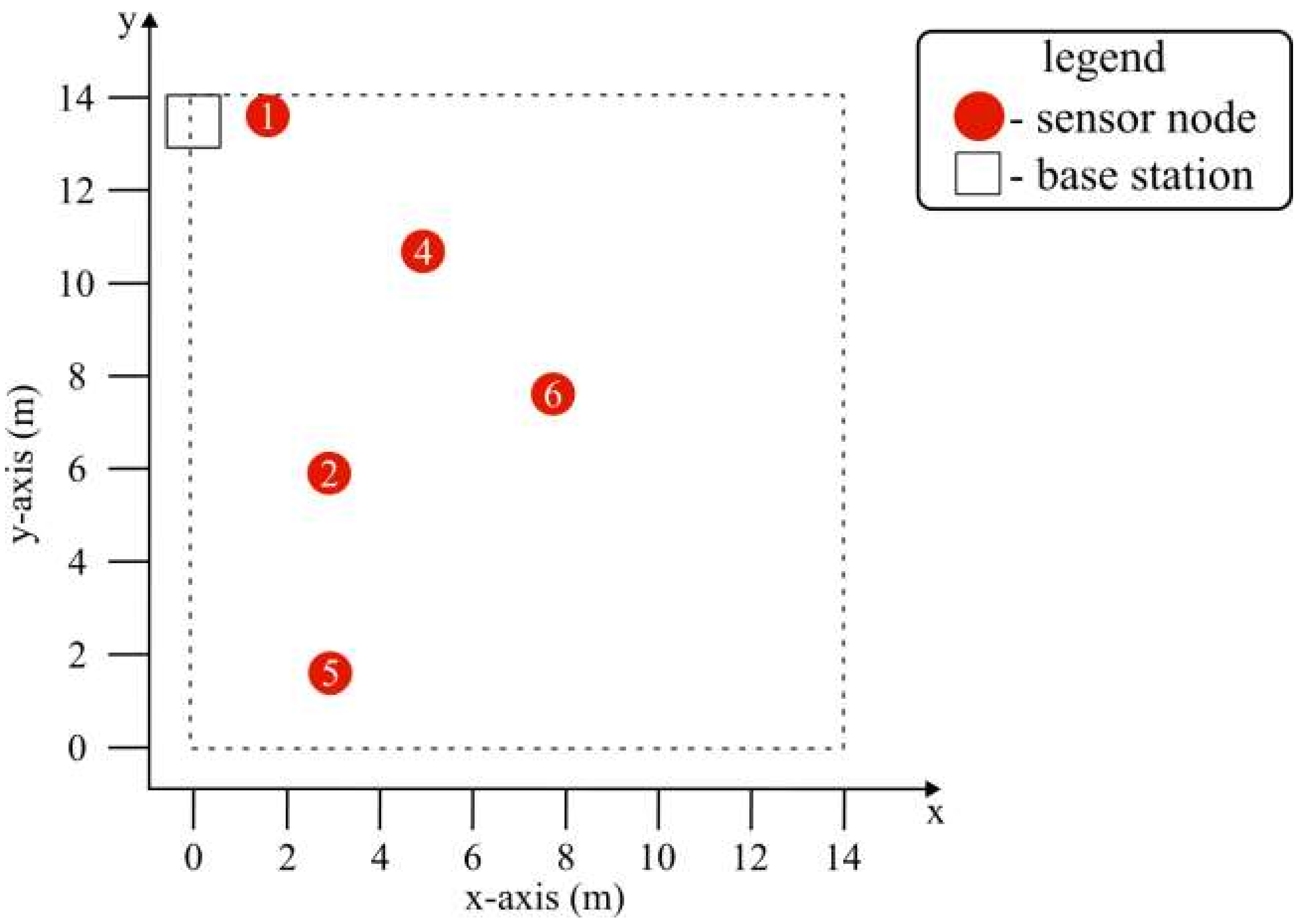
Key Components Inside Weatherproof Compact IoT Base Station Enclosure

- RF Antenna: Facilitates wireless communication with remote sensor nodes.
- Arduino Nano: A microcontroller used for data processing and control tasks.
- nRF24L01+ Module: A high-speed transceiver designed for low-power wireless data transmission.
- Custom PCB: Integrates the Arduino and the transceiver for enhanced connectivity.
- Buck Converter: Regulates voltage to ensure safe power delivery to components.
- Raspberry Pi: Serves as a central hub for data collection, storage, and network management.



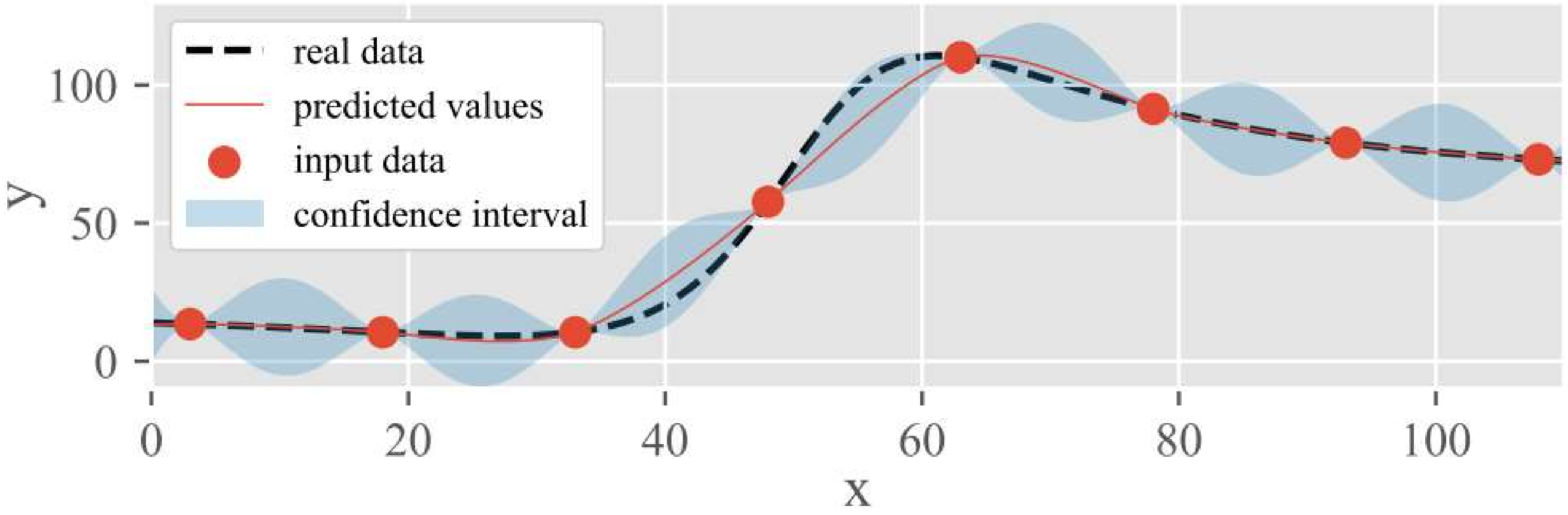
Wireless Sensor Network Layout Overview

- Monitored Region is square area (14m × 14m) enclosed by a dashed border, representing the sensor deployment zone.
- Six red circular markers labeled 1 through 6 (excludes node 3).
- Randomly distributed within the monitored region
- Base Station represented by a white square and located near the top-left corner of the region



Spatial Prediction Using Kriging and

- Kriging: geostatistical interpolation method widely used in mining & environmental sciences.
- Based on regionalized variable theory:
  - Closer data points are more correlated than distant ones.
  - Variance structure captured by a variogram.



Universal Kriging

- Accounts for global trends (e.g., roughness increases with laser power).
- Captures both broad effects and local variability.

- A spatially continuous process Z at a location x represented as:

$$z(x) = \mu(x) + \epsilon(x)$$

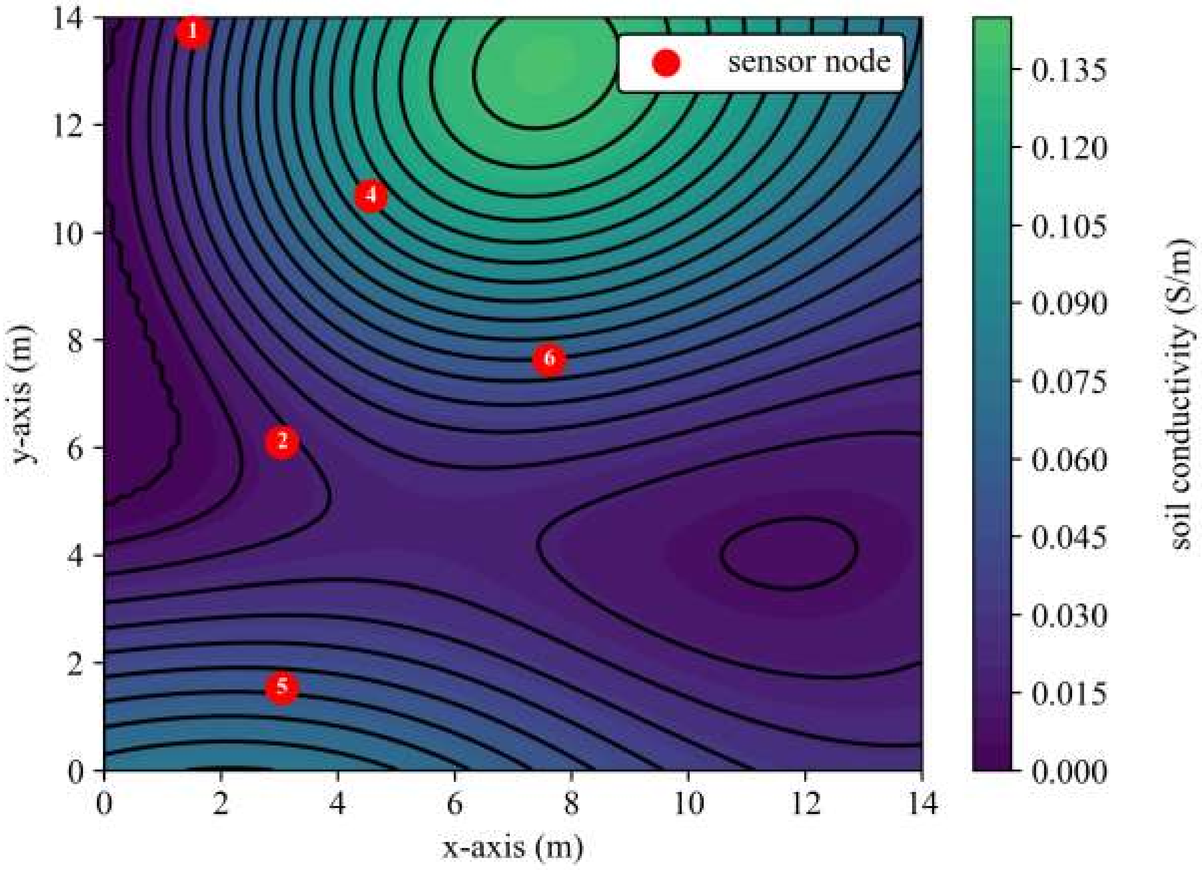
- In matrix notation, the estimated value $\hat{z}(x_0)$ can be solved for as:

$$\hat{z}(x_0) = q_0^{\mathrm{T}} \cdot \hat{\beta} + \lambda_0^{\mathrm{T}} \cdot \epsilon$$

where
  - q_0 is a vector of the predictors at x_0.
  - $\hat{\beta}$ is a vector that contains the estimated drift term coefficients.
  - λ_0 is a vector of n kriging weights determined by the covariance function.
  - ϵ is a vector that contains all the regression residuals (solved iteratively).

Soil Conductivity Distribution with Sensor Node Placement

- Contour map visualizing soil conductivity across a spatial.
- Color Gradient ranges from dark purple (low conductivity) to bright green (high conductivity).
- Indicates conductivity values from approximately 0.045 to 0.135 S/m.



Case Studies #3

Sensor-Based Moisture Monitoring Across Soil Types

- Exploration of volumetric water content and electrical conductivity of clay, silt, and sand samples in wooden-framed soil plots.

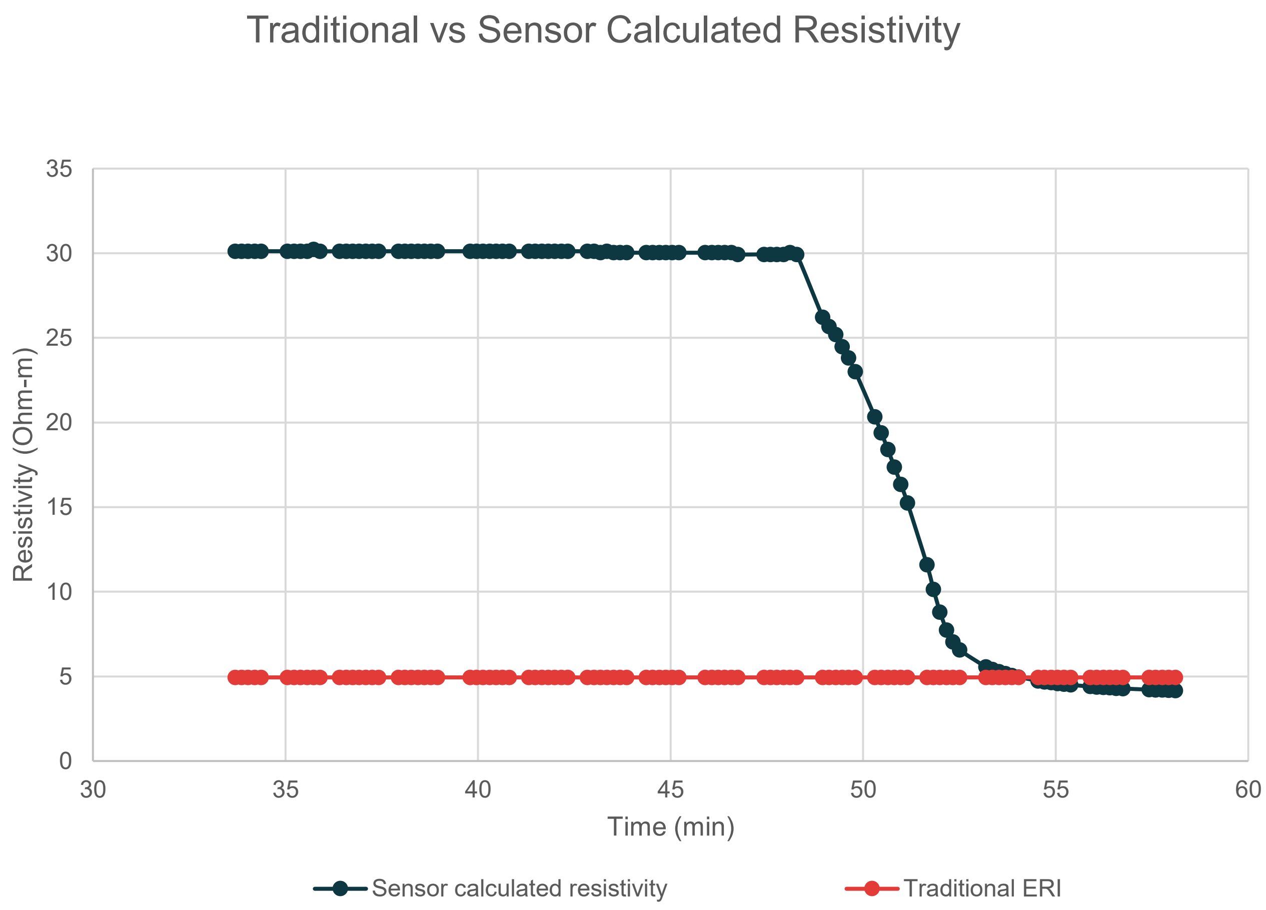
Saturation of soil with Electrolyte

Installed Sensors

Existing 4 pin ERI

Comparison of Sensor 2 with a Traditional ERI

- Sensor calculated resistivity represented by a dark teal line with circular markers.
- Starts at ~30 Ohm·m and remains stable until 45 min then sharp drop to ~5 Ohm·m between 45–50 min, then stabilizes.
- Traditional ERI method represented by a red line with square markers
- Constant resistivity of ~5 Ohm·m throughout the entire time range
- Sensor converges after 45 minutes with the traditional ERI resistivity, suggesting delayed but accurate readings.



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Discussion

GitHub Repository

https://github.com/ARTS-Laboratory/Smart-Penetrometer-with-Edge-Computing-and-Intelligent-Embedded-Systems

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