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Wireless Sensor Network-Based Smart Agriculture Monitoring and Control System

Isandro Ilankovan

Department of Electrical and Computer Engineering, Angkor Mekong Technical University, Cambodia
isandro.ilankovan@amtu-kh.edu

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Abstract

Agricultural production increasingly requires timely information on soil and microclimatic conditions while reducing water, labor, and energy use. This methodology paper proposes a wireless sensor network (WSN)-based smart agriculture monitoring and control system for small and medium farms. Distributed sensor nodes measure soil moisture, soil or ambient temperature, relative humidity, and light intensity; readings are transmitted through a low-power wireless network to a coordinator and gateway. A rule-based decision layer evaluates the measurements and automatically switches an irrigation pump or solenoid valve when soil moisture crosses crop-specific thresholds. The methodology combines hardware selection, node deployment, network communication, data validation, control logic, logging, and a simulation-based evaluation. Literature published up to 2018 is used to justify the architecture and design choices. In a three-day illustrative water-balance simulation, the threshold-driven controller required three irrigation events and 18 L of water compared with five scheduled events and 30 L in a fixed-time baseline, corresponding to a 40% reduction in applied water while maintaining the modeled soil-moisture threshold. The results are methodological and simulation-based rather than claims of field-trial performance. The proposed framework provides a reproducible basis for implementing and experimentally validating low-cost WSN-enabled precision irrigation and crop-environment monitoring.

Introduction

Smart agriculture applies sensing, communication, computation, and automatic control to improve the timing and precision of farm operations. Conventional irrigation commonly depends on fixed schedules or manual observation; both approaches can over-irrigate when soil water remains adequate or under-irrigate during periods of high crop demand. Wireless sensing provides an alternative because environmental data can be collected from multiple points without long signal cables and can be integrated with actuators for closed-loop

control. Early agricultural WSN work established that wireless nodes can support environmental monitoring, precision agriculture, machine control, and traceability, while also identifying energy consumption, radio reliability, and cost as major deployment constraints (Wang et al., 2006).

Irrigation is an especially suitable application because soil moisture varies spatially and temporally, and the value of a measurement increases when it can immediately influence a control decision. Kim et al. (2008) demonstrated distributed sensing and real-time control for site-

specific irrigation, while Vellidis et al. (2008) showed that a dense wireless array can provide field-scale soil-water information for irrigation scheduling. Subsequent systems combined soil-moisture sensing with remote communication and automated pump control (Gutiérrez et al., 2014). These studies show that the key research problem is not only sensing: a useful smart agriculture system must reliably connect sensing, communication, decision logic, actuation, and user supervision.

The objective of this paper is therefore to present a concise, reproducible methodology for developing a WSN-based monitoring and control system that measures soil and atmospheric variables, sends data to a gateway, makes threshold-based irrigation decisions, and records the resulting system response. The paper is intentionally methodology-centered. Its result section reports outputs from a transparent simulation used to verify the control logic, not fabricated field observations. All cited references are from 2018 or earlier, as required.

Literature Review

Agricultural WSN research evolved from general wireless sensing toward integrated precision-agriculture systems. Wang et al. (2006) reviewed wireless technologies for agriculture and emphasized the potential of short-range low-power networks and cellular links for monitoring and process control. Kim et al. (2008) then presented a distributed network connected to a variable-rate irrigation controller, demonstrating the feasibility of combining field sensors with real-time actuation. In the same period, Vellidis et al. (2008) developed a real-time wireless smart sensor array for soil moisture and temperature, while López Riquelme et al. (2009) deployed several mote types in a horticultural farm and showed that WSN infrastructure can collect agronomic data over distributed areas.

The sensing scope later expanded beyond basic irrigation variables. Lloret et al. (2011)

incorporated image-processing nodes into a vineyard WSN to detect abnormal leaf conditions, illustrating how local computation can reduce unnecessary network traffic. A broader review by Aqeel-ur-Rehman et al. (2014) grouped agricultural sensor applications and highlighted challenges including power, limited computation, memory, and communication reliability. Gutiérrez et al. (2014) provided an important closed-loop example by linking root-zone soil-moisture and temperature sensors with automated irrigation and GPRS-based remote access.

By 2015–2018, research increasingly emphasized deployment quality, low cost, energy efficiency, and IoT integration. Ojha et al. (2015) reviewed agricultural WSN practices and identified communication technology, hardware, energy management, scalability, and field robustness as central design challenges. Flores et Kumar and Ilango (2018) reviewed WSN use in precision agriculture and compared communication options such as ZigBee, Bluetooth, Wi-Fi, and cellular systems, while John et al. (2018) further showed that synchronized sleep/wake scheduling and stable routing can improve energy efficiency in a multi-node farm deployment.

The literature therefore supports four design principles adopted here: (1) monitor soil moisture as the primary irrigation variable while collecting microclimate variables for context; (2) use a low-power local WSN, with a gateway bridging field nodes to storage or remote interfaces; (3) keep field nodes energy-aware through periodic sampling and sleep modes; and (4) place the irrigation decision close enough to the field gateway that control can continue even when Internet connectivity is unavailable. The proposed architecture operationalizes these principles in a compact methodology suitable for laboratory prototyping and later field validation.

Table 1. Proposed system components and methodological role

Subsystem	Example element	Measured/controlled variable	Methodological purpose
Sensor node	Capacitive moisture sensor + temperature/humidity + light sensor	Soil moisture, RH, temperature, illumination	Collect spatially distributed crop-environment data
Embedded controller	Low-power microcontroller	Sampling, calibration, packet creation	Local processing and sleep/wake operation
Wireless link	IEEE 802.15.4/ZigBee-class radio	Sensor packets and acknowledgements	Low-power field communication

Coordinator/gateway	Coordinator + Raspberry Pi/PC-class gateway	Node aggregation, timestamping, data storage	Bridge WSN to control and user interfaces
Control stage	Relay/driver + pump or solenoid valve	Irrigation ON/OFF	Convert decisions into physical water delivery
User layer	Local dashboard or mobile/web interface	Alerts, trends, manual override	Supervision, records, and safe override

Methodology

Step 1: Define monitoring requirements and field zones

The field is first divided into management zones according to crop type, soil texture, elevation, or irrigation line. At least one sensor node is placed in each representative zone. The primary control variable is volumetric soil moisture or a calibrated relative moisture percentage at root depth. Ambient temperature and relative humidity provide context for evapotranspiration demand, while a light sensor helps distinguish daytime and nighttime operating conditions. Before deployment, the moisture sensor is calibrated using dry and wet reference points, and the acceptable crop-specific operating band is defined. For the methodology demonstration, the lower irrigation threshold is set to 31.5% relative moisture; the value is illustrative and must be replaced by a crop- and soil-specific threshold during field experiments.

Step 2: Construct and program the sensor nodes
Each node contains the selected sensors, a low-power microcontroller, a wireless transceiver, and a regulated battery or solar-supported supply. The firmware follows a duty-cycled sequence: wake, stabilize sensors, acquire readings, apply calibration, perform range checks, create a packet containing node ID and measurements, transmit the packet, wait briefly for acknowledgement, and return to sleep. A nominal 10–15-minute sampling interval is suitable for irrigation monitoring because soil moisture normally changes much more slowly than radio or processor timescales. John et al. (2018) showed the value of periodic sleep/wake scheduling in an agricultural WSN, and energy-aware sampling is therefore treated as a core requirement rather than an optional optimization.

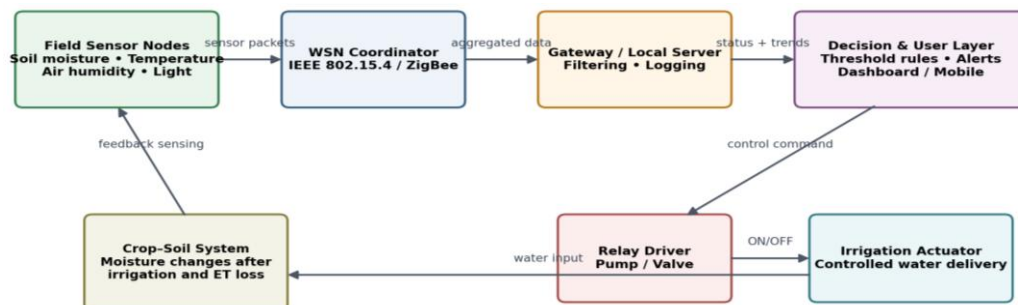


Figure 1. Proposed closed-loop architecture for WSN-based monitoring and automatic irrigation control.

Step 3: Establish the WSN topology and communication protocol

A star topology is preferred for a small farm where all nodes are within radio range of the coordinator; a tree or multi-hop topology can be used when field dimensions, vegetation, or terrain cause link attenuation. Packets include node ID, timestamp or sequence number, sensor values, battery level, and a checksum. The coordinator stores the last valid packet from each node and flags missing updates after a defined timeout. Link testing is performed before irrigation automation is enabled: packet delivery ratio, received signal stability, and retransmission frequency are measured at proposed node locations. The communication

choice is consistent with earlier agricultural WSN literature, which identifies low-power short-range protocols as appropriate for frequent low-volume environmental sensing (Aqeel-ur-Rehman et al., 2014; Kumar & Ilango, 2018).

Step 4: Configure gateway, database, and farmer interface

The coordinator forwards validated packets to a gateway or local server. The gateway timestamps readings, stores them in a structured table, calculates short moving averages to reduce transient noise, and exposes a simple dashboard. The dashboard should display the latest value from every node, historical trends, pump state, communication alarms, and battery warnings. Local storage is important because the irrigation

controller should remain functional during an Internet outage. Remote cloud synchronization may be added when connectivity is available, as illustrated by Raspberry-Pi and IoT-oriented precision-agriculture architectures (Flores et al., 2016; Kiani & Seyyedabbasi, 2018).

Step 5: Implement irrigation decision and safety logic

The control algorithm uses the filtered moisture reading from the active management zone. When moisture falls below the lower threshold, the gateway commands the relay to start irrigation. Irrigation is stopped after a defined pulse duration or when the moisture response reaches an upper safety limit. To prevent rapid switching, a hysteresis margin and a minimum OFF time are imposed. The controller also checks communication freshness; if no valid sensor packet is received within the timeout, automatic watering is inhibited and an alert is generated. A manual override remains available to the operator. This closed-loop arrangement follows the functional direction demonstrated by Kim et al. (2008) and Gutiérrez et al. (2014), but it separates the sensing, gateway, and safety functions so that each can be tested independently.

Step 6: Validate through bench tests and a reproducible simulation

Validation is performed in two stages. First, bench tests verify sensor calibration, packet transfer, relay switching, timeout handling, and manual override. Second, a simple water-balance simulation verifies that the threshold rule behaves as intended before field deployment. The simulation covers three days at 30-minute intervals, begins at 36% relative soil moisture, and imposes a diurnal moisture-loss function representing higher daytime evapotranspiration. Each irrigation event adds 3.5 percentage points to the modeled moisture and uses 6 L of water. The WSN controller irrigates only when moisture falls below 31.5%. The baseline uses the same event volume but irrigates every 12 hours. Because the model is deterministic and explicitly stated, the numerical outputs are reproducible and are not presented as measured agronomic performance.

For the subsequent field-validation stage, the experiment should run long enough to include multiple wetting and drying cycles. A reference soil-moisture instrument is placed beside at least one network node so that sensor bias and

repeatability can be quantified. The gateway log is compared with the reference record using mean absolute error and root-mean-square error. Network performance is evaluated from transmitted sequence numbers: packet delivery ratio is calculated as successfully received packets divided by expected packets, and latency is measured from node transmission to gateway acceptance. The actuator test records command time, relay response, flow-sensor response, and pump shutdown time. These tests separate sensing error, communication loss, and hydraulic delay rather than treating the system as a single black box.

Acceptance criteria are defined before deployment to prevent selective interpretation of results. A practical prototype target is at least 95% packet delivery under normal field conditions, no uncontrolled pump activation after a communication timeout, and stable sensor calibration over the test interval. Irrigation performance is evaluated using total water delivered, number and duration of irrigation events, time spent below the lower moisture limit, and time spent above an upper moisture limit that may indicate over-watering. Energy performance is estimated from node current in sensing, transmit, receive, and sleep states and is checked against measured battery discharge. The resulting dataset therefore supports both agronomic and engineering assessment, which is important because a system that saves water but has unreliable communication or short battery life would not be operationally suitable.

Results

The simulation produced 3 threshold-triggered irrigation events for the WSN controller and 5 scheduled events for the fixed-time baseline. Total modeled water use was 18 L and 30 L, respectively, giving a calculated reduction of 40%. The minimum modeled moisture under the WSN controller was 31.5%, which remained at or just above the configured control threshold after each discrete update. The fixed schedule maintained a higher average moisture (38.5% compared with 33.7%) but achieved this by applying more water than the threshold-based method required in the model. This is the expected behavioral advantage of feedback control: irrigation is linked to measured need rather than elapsed time.

Table 2. Simulation-based control results (illustrative methodological validation, not field measurements)

Metric	WSN threshold control	Fixed 12-hour schedule	Interpretation
Irrigation events	3	5	Feedback avoids unnecessary scheduled events

Water applied	18 L	30 L	40% lower in the stated simulation
Minimum modeled moisture	31.5%	34.0%	Both remain above the intended stress boundary in this model
Mean modeled moisture	33.7%	38.5%	Fixed scheduling maintains excess moisture at higher water use
Control trigger	Moisture < 31.5%	Clock every 12 h	Sensor-driven versus time-driven control

The results do not establish crop-yield improvement because no biological field trial was assumed. They instead confirm three engineering properties of the proposed method. First, the control rule is deterministic and can be tested independently of the radio network. Second, sensor-driven irrigation can reduce unnecessary actuation when the measured state remains inside the desired range. Third, a gateway-level controller provides a natural place to enforce safety checks such as sensor freshness, hysteresis, maximum pump duration, and manual override. These properties are consistent with the direction of prior WSN irrigation research, in which real-time sensing is valuable principally because it enables more responsive water management (Vellidis et al., 2008; Gutiérrez et al., 2014).

For an actual field experiment, the same table should be extended with measured packet delivery ratio, end-to-end latency, sensor error against reference instruments, daily energy consumption, battery life, irrigation volume measured by a flow sensor, and crop-response variables. The literature shows that field robustness and network energy remain critical practical issues: López Riquelme et al. (2009) emphasized range and robustness during farm deployment, Ojha et al. (2015) highlighted hardware and networking challenges across agricultural WSNs, and John et al. (2018) demonstrated the importance of energy-balanced data collection. These metrics should therefore be treated as mandatory validation outcomes in the next experimental phase.

A sensitivity check is also necessary before interpreting water savings. The numerical saving depends on the lower moisture threshold, irrigation pulse volume, modeled evapotranspiration, soil water-holding capacity, and the baseline schedule. In the present deterministic example, the control threshold is used only to verify logical behavior; it is not an agronomic recommendation. During a field trial, threshold values should be established from crop rooting depth, soil texture, allowable depletion, and calibrated sensor response. Repeating the analysis across several thresholds would show

whether the controller remains stable and whether reported water savings persist across realistic parameter uncertainty.

The proposed system has additional implementation risks. Wireless links can be shadowed by vegetation or wet foliage, sensor probes may drift because of salinity and soil contact, and relay or pump failures can produce a control state that differs from the software command. For this reason, the final prototype should include acknowledgement of actuator state, maximum-run timers, protected electrical switching, and a fail-safe default that turns irrigation off when control information is stale. The farmer interface should distinguish a low-moisture alarm from a communication alarm so that corrective action is appropriate. These safeguards transform the design from a monitoring demonstration into a controllable agricultural system.

Conclusion and Discussion

This paper presents a step-by-step methodology for a WSN-based smart agriculture monitoring and control system in which distributed nodes sense soil and environmental conditions, a low-power network transports the data, a gateway validates and stores measurements, and a rule-based controller operates an irrigation actuator. The architecture is grounded in agricultural WSN research published no later than 2018 and reflects the progression from wireless monitoring to integrated sensing, decision support, and control. The methodology deliberately keeps automatic control local so that basic irrigation can continue without dependence on cloud connectivity, while still allowing remote visualization and alerts when Internet access is available. The simulation illustrates the intended control behavior rather than claiming empirical farm performance. Under the stated assumptions, threshold-based irrigation used 18 L instead of 30 L over three days, a 40% reduction, while preserving the configured moisture floor. This supports the rationale for a field trial but does not substitute for one. Future implementation should calibrate thresholds for the specific soil and crop, measure hydraulic

response and sensor uncertainty, quantify packet delivery and battery lifetime across seasons, and compare water use, energy use, yield, and crop quality against conventional irrigation. Security and authentication should also be added before remote control is exposed beyond the local farm network. With these validations, the proposed methodology can serve as a practical platform for low-cost precision irrigation and scalable smart-farm monitoring. From a research-method perspective, the principal strength of the framework is modularity. Sensor accuracy, radio performance, control logic, actuator behavior, and agronomic response can be evaluated with separate metrics and then integrated into an overall assessment. This makes failures easier to diagnose and supports replication with different hardware platforms. Its main limitation is that threshold control is simpler than crop models or predictive irrigation approaches; however, that simplicity is useful for a first validated prototype because the cause of every control action remains transparent. Once field reliability is established, weather forecasts, evapotranspiration estimation, multi-zone control, and adaptive thresholds can be added without changing the fundamental sensing-to-gateway architecture.

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