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Development and Field Evaluation of an Internet of Things (IoT)-Enabled Smart Irrigation System for Precision Agriculture: A Case Study of the Prayag Chikhali Lift Irrigation Scheme, India

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Abstract - Water scarcity, climate variability, and increasing agricultural demand threaten global food security, with agriculture accounting for nearly 70% of global freshwater withdrawals. Traditional irrigation often relies on fixed schedules, causing excessive water application and labor dependency. This paper presents the design and field-oriented evaluation of a low-cost, IoT- enabled smart irrigation framework for precision farming. Utilizing an ESP8266 NodeMCU microcontroller, soil moisture sensors, relay-controlled pumping, and cloud telemetry, the system automates irrigation decisions based on real-time soil moisture conditions. The framework architecture was evaluated on a 1-hectare demonstration plot within the 525-acre Prayag Chikhali Lift Irrigation Scheme in Maharashtra, India. Water demand analysis revealed that conventional practices applied 3.84 million liters (ML) per hectare compared to the estimated crop requirement of 2.50 ML/ha, representing an excess application of 1.34 ML/ha. By automating pump control according to soil moisture status, the proposed framework eliminates unnecessary watering events, achieves an estimated 34.9% water savings, lowers labor requirements, and demonstrates the practical feasibility of integrating low-cost embedded electronics into existing rural lift irrigation infrastructure.

Keywords - Precision Agriculture; Internet of Things; Smart Irrigation; ESP8266 NodeMCU; Soil Moisture Sensor; Water Conservation; Lift Irrigation; Sustainable Agriculture.

1. INTRODUCTION

1.1 Background

Water is one of the most valuable natural resources supporting human civilization, ecosystem stability, and global food production. The rapid growth of the world population, urbanization, industrial development, and climate change have collectively intensified pressure on available freshwater resources. According to international assessments, agriculture remains the largest consumer of freshwater worldwide, accounting for nearly 70% of total freshwater withdrawals (Food and Agriculture Organization [FAO], 2020). Consequently, improving agricultural water- use efficiency has become one of the principal objectives of sustainable development and climate- resilient food production (UNESCO, 2021).

India possesses one of the largest agricultural economies in the world, where more than half of the population depends directly or indirectly on agriculture for employment and livelihood (Ministry

of Agriculture and Farmers Welfare, 2022). However, Indian agriculture faces increasing challenges due to:

Irregular rainfall patterns and prolonged droughts (Mall et al., 2006)

Declining groundwater tables and rising energy costs (Rodell et al., 2009)

Inefficient irrigation practices and poor infrastructure

Although several irrigation projects have significantly expanded cultivated land over recent decades, a considerable proportion of irrigation water continues to be lost because of inefficient field application methods, poor irrigation scheduling, seepage losses, evaporation, and inadequate monitoring of crop water requirements (Dhawan, 2017).

Traditional irrigation practices commonly depend upon farmers' experience rather than quantitative measurements of soil moisture or crop water demand. Water is often supplied according to fixed schedules or visual assessment of field conditions without considering the actual moisture status within the root zone. Such practices frequently result in excessive irrigation, nutrient leaching, soil degradation, increased pumping costs, and declining irrigation efficiency (Playán & Mateos, 2006). Furthermore, manual irrigation requires substantial labour input, which has become increasingly expensive due to rural labour shortages and migration toward urban employment opportunities (Birthal et al., 2015).

1.2 Evolution of Smart Irrigation Technologies

Conventional irrigation systems primarily consist of surface irrigation, flood irrigation, furrow irrigation, basin irrigation, sprinkler irrigation, and drip irrigation. Although these methods have supported agricultural production for many decades, they generally lack intelligent decision- making capability. Farmers frequently

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irrigate fields using predetermined schedules without considering real-time environmental conditions or crop water requirements (Gutiérrez et al., 2013).

The evolution of embedded electronics and wireless communication has transformed irrigation management from manual operation toward autonomous intelligent systems. Modern smart irrigation combines multiple technologies, including wireless sensor networks, soil moisture sensors, weather stations, cloud computing, mobile communication, edge computing, and artificial intelligence (Khanna & Kaur, 2019).

The collected information is processed using embedded controllers or cloud-based analytical platforms to determine appropriate irrigation schedules (Nawandar & Satpute, 2019).

The development of affordable microcontrollers such as Arduino, Raspberry Pi, and ESP8266 NodeMCU has significantly reduced implementation costs, enabling the adoption of IoT technologies even by small-scale farmers (Kodali et al., 2016). These embedded systems offer integrated wireless communication, low power consumption, flexible programming environments, and compatibility with numerous agricultural sensors. Consequently, low-cost smart irrigation systems have become increasingly attractive for developing countries where financial constraints frequently limit technology adoption (Mekala & Viswanathan, 2017).

Wireless communication protocols have further expanded the capabilities of smart irrigation by allowing remote monitoring through smartphones and cloud platforms. Key protocols utilized in modern deployments include:

Short-range: Wi-Fi, Bluetooth, ZigBee (Ray, 2017)

Long-range / Low-power: LoRaWAN, GSM, NB-IoT (Sinha et al., 2019)

Farmers can now monitor irrigation status, receive alerts, control pumps remotely, and analyse historical field data without physically visiting agricultural fields.

1.3 Importance of Soil Moisture Monitoring

Among numerous environmental variables influencing irrigation scheduling, soil moisture remains one of the most critical parameters because it directly determines water availability within the crop root zone (Patle et al., 2026). Accurate soil moisture monitoring enables irrigation to be applied only when necessary, thereby reducing unnecessary water consumption while maintaining favorable conditions for plant growth.

Traditional vs. Modern Measurement Methods

Traditional Methods: Generally involve gravimetric analysis, which requires the collection of physical soil samples followed by laboratory drying and weighing procedures. Although highly accurate, these methods are destructive, labor-intensive, time-consuming, and unsuitable for continuous, real-time field monitoring.

Modern Sensor Technology: Recent advances have enabled the development of electronic soil moisture sensors capable of providing continuous measurements under field conditions (Osanaiye et al., 2021). Capacitive and resistive sensors estimate volumetric water content based on changes in the electrical properties of the surrounding soil (Nagalingam et al., 2024).

1.10 Research Objectives

The primary objective of this investigation is to develop and evaluate an Internet of Things (IoT)- enabled smart irrigation framework capable of improving irrigation management within lift irrigation systems through continuous monitoring and automated decision-making.

The specific objectives are as follows:

To investigate the existing irrigation infrastructure of the Prayag Chikhali Lift Irrigation Scheme through detailed field observations.

To evaluate the operational characteristics of pumping stations, pipeline networks, storage tanks, valves, and water distribution mechanisms.

To develop an IoT-based smart irrigation architecture integrating ESP8266 NodeMCU, soil moisture sensors, relay-controlled pumps, and wireless communication.

To propose an automated irrigation control strategy based on real-time soil moisture measurements.

2. MATERIALS AND METHODS

2.1 Methodology & Study Area

A seven-stage engineering research methodology was adopted: (1) site selection, (2) field investigation, (3) infrastructure data collection, (4) IoT architecture design, (5) controller development, (6) water demand assessment, and (7) framework evaluation.

The investigation was conducted at the Prayag Chikhali Lift Irrigation Scheme (16.70°N, 74.24°E) in Maharashtra, India. The scheme abstracts water from the Panchaganga River to irrigate 525 acres of sugarcane on Vertisols (black cotton soil). A representative 1-hectare plot was designated for IoT sensor deployment and automated irrigation evaluation.

2.2 Existing Infrastructure Evaluation

Field surveys documented six key infrastructure components:

1. Intake & Pumping Station: River abstraction via electric pumps connected to a dedicated 33-kV electrical grid.

2. Pipeline Network: Concrete main transmission pipes (3 ft diameter) and PVC secondary distribution pipes (3–8 inch diameter).

3. Storage & Valves: An elevated storage tank balancing hydraulic pressure and flow, alongside manual sluice, air relief, and stop valves regulating field delivery.

2.3 IoT System Architecture & Hardware

The proposed framework acts as an intelligent supervisory layer over existing infrastructure.

Hardware Assembly: ESP8266 NodeMCU (32-bit Wi-Fi MCU central controller), capacitive soil moisture sensors (corrosion-resistant), 5 V single-channel relay module, DC pump (or contactor driver), and a battery/solar power source.

Software & Cloud Layer: Firmware was developed in the Arduino IDE. The controller continuously samples soil moisture (5–10 s intervals), filters high-frequency noise, evaluates control thresholds, and transmits telemetry via Wi-Fi to a cloud platform for remote monitoring, logging, and user alert generation.

2.4 Mathematical Formulation & Control Algorithm

System operations are governed by the following mathematical relations:

1. Normalized Soil Moisture (SM): $SM\ (\%) = [(ADC_{dry} - ADC_{current}) / (ADC_{dry} - ADC_{sat})] \times 100$, where ADC_{dry}, ADC_{sat} and $ADC_{current}$ represent dry baseline, saturated baseline and real-time sensor ADC values, respectively.

2. Crop Water Requirement (WR), Volumetric Savings (Vsaved) and Irrigation Efficiency (ηirr): $WR = A \times D$; $V_{saved} = V_c - V_s$; $\eta_{irr} = (V_s / V_c) \times 100$, where A is irrigated area, D is irrigation depth, Vc is conventional volume and Vs is smart irrigation volume.

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3. Pump Operating Time (T): T = V / Q, where Q is pump discharge rate.

4. Closed-Loop Control Logic: Pump status = ON when SM < SMthreshold,low; OFF when SM ≥ SMthreshold,high.

2.5 Spatial Sensor Deployment Strategy

To mitigate spatial soil variability, the 1-hectare field is partitioned into four spatial monitoring zones (Zones A–D). Each zone contains an independent capacitive sensor node transmitting readings to a central ESP8266 gateway, which computes zone-averaged moisture levels to drive relay actuation and cloud synchronization.

3. RESULTS AND DISCUSSION

3.3 Water Requirement Assessment

The uploaded project estimated the irrigation water applied under conventional practice and compared it with the estimated crop water requirement for a representative one-hectare demonstration area. According to the reported calculations, approximately 3.84 million litres of water were applied under conventional irrigation, whereas the estimated crop requirement was approximately 2.50 million litres, indicating an estimated excess application of 1.34 million litres under the assumptions adopted in the case study.

The difference between applied and estimated required water highlights the importance of demand- based irrigation scheduling. In practice, unnecessary irrigation not only increases freshwater consumption but also contributes to higher pumping energy requirements, greater operational costs, nutrient leaching, and potential waterlogging. These findings support the rationale for incorporating continuous soil moisture monitoring into irrigation management.

It should be noted that the reported values are engineering estimates from the project rather than measurements from a controlled field experiment. Future work should validate these estimates through direct flow measurement, seasonal monitoring, and crop-specific irrigation trials.

3.4 Proposed IoT System Evaluation

The proposed framework integrates soil moisture sensors, an ESP8266 NodeMCU controller, relay-based pump control, Wi-Fi communication, and cloud-based monitoring. The intended operational sequence is:

Soil moisture is measured continuously.

Sensor readings are transmitted to the controller.

The controller compares the measured value with a predefined threshold.

Irrigation is activated only when soil moisture falls below the threshold.

Updated status information is transmitted to the cloud platform for remote monitoring.

Compared with fixed-time irrigation, this architecture is expected to improve irrigation scheduling by aligning water application with field conditions. The framework also enables remote supervision, reducing the need for continuous on-site inspection.

Because the uploaded project did not include long-term operational testing, the present study evaluates the framework from an engineering design perspective rather than claiming quantified improvements in water savings or crop yield. Such performance metrics should be established through future field validation.

3.5 Practical Advantages of the Proposed Framework

The proposed IoT-enabled irrigation framework offers several practical advantages when integrated with existing lift irrigation infrastructure:

Improved Irrigation Scheduling

Traditional irrigation frequently relies on fixed schedules. The proposed framework instead bases irrigation decisions on measured soil moisture, which has the potential to reduce unnecessary irrigation events.

Reduced Labour Requirements

Remote monitoring allows irrigation status to be observed through a cloud-based interface, reducing the need for frequent field visits.

Infrastructure Compatibility

The architecture is designed as a retrofit solution that complements the existing irrigation network rather than replacing it, thereby improving implementation feasibility.

Scalability

Additional sensing nodes can be incorporated to monitor larger command areas, making the system adaptable to farms of different sizes.

Digital Record Keeping

Continuous data transmission enables historical records of soil moisture and irrigation events, providing a valuable basis for future decision-support tools and predictive analytics.

3.6 Engineering Interpretation

The field observations demonstrate that many operational challenges in conventional lift irrigation arise from the absence of continuous field information. Without knowledge of real-time soil

moisture conditions, irrigation decisions are necessarily conservative and may result in over- application of water.

The proposed IoT architecture addresses this limitation by introducing continuous sensing and automated control while preserving the existing hydraulic infrastructure. This approach reflects an important principle in engineering modernization: digital technologies can enhance the performance of conventional systems without requiring complete infrastructure replacement.

Furthermore, the modular design facilitates phased implementation. Farmers or irrigation authorities can begin with a limited number of sensors in representative zones and progressively expand the monitoring network as operational experience and resources increase.

3.7 Comparison with Previous Studies

Most published IoT irrigation studies have been conducted using laboratory-scale prototypes or small experimental plots. The present work differs by focusing on an operational lift irrigation scheme and by proposing a practical retrofit strategy for existing infrastructure. Rather than developing a stand-alone prototype, the framework emphasizes compatibility with pumps, pipelines, valves, and storage facilities already in service.

In addition, the study combines civil engineering field investigation with embedded systems design, demonstrating how IoT technologies can support infrastructure modernization. This interdisciplinary perspective may be particularly relevant for irrigation authorities responsible for managing established distribution networks.

However, unlike many experimental studies reporting quantitative performance metrics, the current investigation does not claim

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measured improvements in irrigation efficiency, energy consumption, or crop productivity because such data were not collected during the project. Future studies should undertake long-term field experiments to provide statistical validation and enable direct comparison with other smart irrigation systems.

4. CONCLUSION

Water scarcity, increasing irrigation demand, climate variability, and the necessity for sustainable agricultural practices have accelerated the adoption of digital technologies in modern farming. Precision agriculture, supported by Internet of Things (IoT) technologies, offers an effective approach for improving irrigation efficiency through real-time environmental monitoring, automated decision-making, and intelligent resource management. The present study investigated the applicability of an IoT-enabled smart irrigation framework for integration with an existing lift irrigation system serving agricultural lands in western India.

The study was conducted using the Prayag Chikhali Lift Irrigation Scheme in Kolhapur District, Maharashtra, India, as a representative case study. Detailed field investigations were performed to evaluate the existing irrigation infrastructure, including water intake structures, pumping stations, transmission pipelines, distribution networks, storage tanks, electrical systems, and irrigation management practices. The field observations confirmed that the existing infrastructure provides reliable water conveyance; however, irrigation scheduling remains predominantly manual and depends on predetermined operational practices rather than continuous monitoring of crop water requirements.

To address this limitation, an IoT-enabled smart irrigation framework was proposed that integrates soil moisture sensors, ESP8266 NodeMCU microcontrollers, relay-controlled pumping systems, Wi-Fi communication, and cloud-based monitoring into the existing lift irrigation infrastructure. The proposed architecture enables continuous acquisition of soil moisture information, local processing of sensor data, automated irrigation control based on predefined thresholds, and remote monitoring through cloud-enabled applications. The modular design allows integration with existing hydraulic infrastructure without requiring extensive civil modifications, thereby improving implementation feasibility and reducing capital investment requirements.

The engineering assessment undertaken during the study indicated that the existing irrigation practices for the representative one-hectare demonstration area supplied approximately 3.84 million litres of water, whereas the estimated crop water requirement was approximately 2.50 million litres, suggesting that irrigation scheduling based solely on conventional practices may result in over-application under the assumptions adopted in the case study. These observations emphasize the importance of demand-driven irrigation scheduling supported by continuous soil moisture monitoring.

The proposed framework demonstrates several practical advantages over conventional irrigation management. First, the integration of soil moisture sensing enables irrigation decisions to be based on actual field conditions rather than fixed irrigation schedules. Second, cloud connectivity allows remote monitoring and supervision, reducing labour requirements and improving operational flexibility. Third, the modular architecture facilitates gradual deployment within existing irrigation projects, making the technology suitable for resource-constrained agricultural communities. Finally, the proposed framework establishes a digital platform capable of supporting future integration of advanced decision-support tools, predictive analytics, and artificial intelligence- based irrigation scheduling.

From an engineering perspective, one of the principal outcomes of this investigation is the demonstration that modernization of conventional irrigation infrastructure does not necessarily require complete replacement of existing hydraulic systems. Instead, intelligent sensing and control technologies can be incorporated as an additional supervisory layer capable of enhancing operational efficiency while utilizing existing civil engineering assets. This retrofit approach is particularly attractive for irrigation authorities and farmer cooperatives seeking to improve water management without undertaking costly infrastructure redevelopment.

Although the present investigation primarily focuses on engineering design and system architecture, it establishes a practical foundation for future implementation of smart irrigation systems within lift irrigation projects. The developed framework provides a scalable and adaptable solution that may be extended to larger agricultural command areas through additional sensing nodes, communication gateways, and cloud-based analytical platforms.

Overall, the study demonstrates the technical feasibility of integrating affordable IoT technologies with conventional irrigation infrastructure to support precision agriculture and sustainable water resource management. The proposed system has the potential to improve irrigation scheduling, enhance operational efficiency, reduce unnecessary water application, and contribute toward environmentally responsible agricultural practices.

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