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AgriFlow: Scalable Real-Time Monitoring and Predictive Modeling for Mitigating Agricultural Nitrogen Runoff

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Abstract - This paper presents AgriFlow, a scalable system for optimizing nitrogen fertilizer use through real-time monitoring and predictive runoff modeling. The platform combines capacitive soil moisture sensors, terrain mapping, and rainfall-based runoff simulations to generate actionable nitrogen loss estimates after rain events. Hardware prototypes achieved ±2% accuracy and reliable RF communication up to 200 meters, with ultra-low power design supporting over 10 years of field operation. A cloud-based backend processes sensor data using the KINEROS2 model and displays runoff forecasts via a web interface. Validation through greenhouse calibration, field trials, and power testing confirmed system accuracy and efficiency. AgriFlow fills a key gap in precision agriculture by dynamically estimating nutrient loss, particularly for sloped fields.

Index Terms - agriculture, fertilizer optimization, IoT sensors, nutrient runoff, predictive modeling, precision farming

I. Introduction

A. Previous Works

Traditional soil testing has long been recognized as a key method for optimizing fertilizer use. However, its adoption remains limited - over 60% of farmers worldwide do not conduct laboratory soil analysis due to its high cost, labor intensity, and delays in obtaining results. The lack of timely soil data leads to uncertainty about nutrient needs, prompting farmers to over-apply fertilizers as a precaution. This widespread inefficiency results in more than 65% of nitrogen fertilizers going unused by crops[2], causing severe ecological and economic consequences - including over 2.6 billion tons of CO_2 emissions annually and approximately $75 billion in wasted fertilizer.

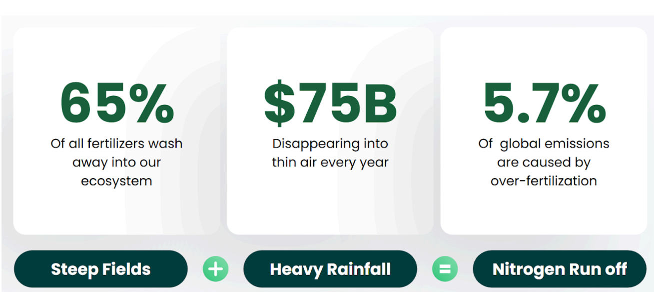

Figure 1: Size of Runoff Problem

Recent efforts to address these inefficiencies include the development of soil moisture sensors, nutrient modeling software, and remote sensing systems. However, these technologies rarely account for real-time hydrological events - particularly runoff on sloped terrain, which can rapidly deplete soil nutrients after rain. Existing commercial tools (e.g., Soiltech, Spiio, SoilSense) focus primarily on measuring moisture levels rather than predicting nutrient mobility.

B. Motivation

Through field observations and user interviews, we identified a critical yet underserved user segment: farmers managing sloped agricultural fields. In these environments, even the most precise pre-season soil testing fails to remain accurate throughout the growing cycle. Rain-induced runoff can alter soil nutrient levels dramatically within hours. Without the ability to model this runoff dynamically, farmers are left uncertain about when and where to reapply fertilizer, leading to unnecessary applications or reduced yield due to under fertilization, especially in nitrogen-sensitive crops.

C. Problem Statement

Current precision agriculture tools do not provide post-rain nutrient estimates for sloped fields. This gap forces affected farmers to rely on guesswork after rain events, undermining the value of soil testing and leading to inefficient fertilizer use.

D. Proposed Solution:

To address this problem, we propose AgriFlow: a scalable, real-time nitrogen runoff prediction platform. AgriFlow integrates capacitive soil moisture sensors, terrain slope mapping, rainfall data, and predictive modeling using the KINEROS2[1] hydrological framework. By combining hardware sensing with cloud-based runoff simulations, the system estimates post-rain nutrient loss, helping farmers make informed decisions on reapplication. This approach is tailored to farmers cultivating high-slope fields and aims to reduce nitrogen waste while increasing yield predictability.

II. Design and Methodology

A. Specifications, Requirements, and Constraints

The AgriFlow system was developed to address a specific set of performance targets, environmental conditions, and user needs, resulting in a clear set of design specifications and constraints. Accurate soil moisture measurement was central to the system's functionality, with sensors required to achieve an accuracy of ±2% to ensure reliable estimation of post-rain nutrient conditions. Communication range was another key consideration, as the sensors needed to operate effectively over fields as large as 10 acres per peripheral, necessitating a minimum 200-meter transmission range between devices.

Given that the sensors are often deployed underground or in exposed field environments, device enclosures were required to be waterproof, resistant to temperature fluctuations, and physically durable. To serve diverse agronomic scenarios, the devices also had to be modular, supporting multiple sensor depths and configurations. On the software side, the system had to provide individualized user access, allowing farmers to log in, select their plots, and receive runoff simulations based on their specific field conditions.

The communication network was designed to support a chained transmission range of up to 10 kilometers using a mesh topology, making the platform scalable across large and complex terrain. Power efficiency was a defining constraint: each peripheral needed to operate autonomously for over seven years using a single 3000 mAh battery. This requirement placed strict limits on measurement frequency, limiting each peripheral to a single 30-second active transmission window per day. In addition, the simulation model had to be grounded in validated hydrological frameworks, with KINEROS2[1] selected as the core engine. The system also had to comply with regulatory requirements, remain affordable for commercial deployment, and integrate seamlessly with modern precision agriculture workflows.

B. Design Procedure and Iterations

The development process underwent several major design iterations, particularly in communication strategy and hardware configuration. The initial prototype used Bluetooth Low Energy (BLE) for short-range data transmission, but this approach was insufficient for the targeted field sizes. A transition to RF communication using the RFM69HCW module provided the required range and reliability. In early versions, SIM modules were embedded in each peripheral to allow direct data transmission to the cloud. However, the high power consumption of these modules—up to 2A per high power transmission—made them unsuitable for long-term, battery-powered operation.

Subsequent iterations focused on synchronizing data transmission between peripherals and a central master node. One early approach was to have peripherals turn on daily to transmit data directly to the master. To address cases where the master was out of range, an intermediary listener node was considered. Another proposed strategy involved a 24-hour setup mode, in which the peripheral remained active throughout the day and synchronized with the master through a secure handshake protocol. However, this approach consumed up to 772.8 mAh per day, rapidly depleting the battery and introducing reliability issues related to system resets and reinitialization.

A more power-efficient and scalable solution was ultimately implemented. During system setup, a user presses a synchronization button on the peripheral and opens their phone to send their current GPS coordinates to the cloud. The master node then retrieves a communication table and transmits routing information back to the peripheral over RF. The peripheral stores time and routing data locally, using a MAX31329ELB+ real-time clock that wakes up the peripheral precisely once per day. The nRF52840 microcontroller receives data from nearby nodes, stores it in onboard flash memory, and transmits it through the shortest available RF mesh path (calculated through a modified prim hop penalty algorithm) to the master.

Hardware development also progressed significantly. The original version consisted of a single moisture sensor paired with an ESP32 Feather microcontroller. This was upgraded to the nRF52840 platform, which supports up to 16 sensors via I^2C, dramatically increasing scalability and reducing energy consumption in sleep mode (the nRF52840 can enter a deep sleep mode of 0.97 µA). Custom PCBs were then designed in Altium and integrated into weatherproof enclosures with modular design elements, allowing for easy manufacturing and adaptation to different field conditions. These hardware refinements were validated through both greenhouse and field testing in collaboration with the University of Pennsylvania Biology Department, where sensor calibration, data accuracy, and communication reliability were verified.

C. System Architecture

The AgriFlow system is structured around three interdependent layers: the hardware sensing layer, the cloud-based data processing layer, and the simulation and visualization interface.

On the software side, the backend is hosted on Amazon Web Services (AWS), with MongoDB Atlas managing sensor data, weather forecasts, and user configurations. A MERN (MongoDB, Express, React, Node.js) frontend provides the user interface, allowing farmers to view sensor locations, receive nitrogen loss estimates, and access field-specific simulations. The frontend includes Google Maps API[3] integration to provide sub-meter spatial resolution for farm mapping and device placement.

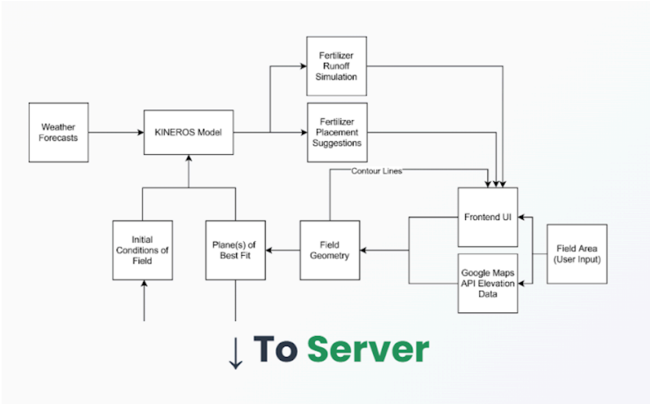

Figure 2: Software Block Diagram

The hardware layer consists of peripheral sensor nodes built around the Seeed Studio nRF52840 microcontroller, paired with RFM69HCW modules for RF communication over SPI. Each node supports up to 16 capacitive moisture sensors via I²C on an ADS1115 interface and includes a MAX31329ELB+ real-time clock to manage wake-up timing. A 3000 mAh LiPo battery powers each unit, designed for long-term deployment. During normal operation, peripherals remain in deep sleep and wake once per day to transmit data, minimizing energy consumption. The master device, built on the ESP32-Feather microcontroller and equipped with a SIM7600G-H 4G communication module, serves as the gateway, relaying sensor data to the cloud via cellular networks.

Data transmission follows a defined flow: peripheral sensors collect moisture data and transmit it over the RF mesh network to the nearest node, which relays the data toward the master using a shortest-path algorithm derived from a modified Prim's hop penalty algorithm. The master node forwards the aggregated data to the cloud, where it is processed by the simulation engine and displayed on the user dashboard. This end-to-end pipeline allows AgriFlow to deliver near-real-time insights without constant sensor connectivity.

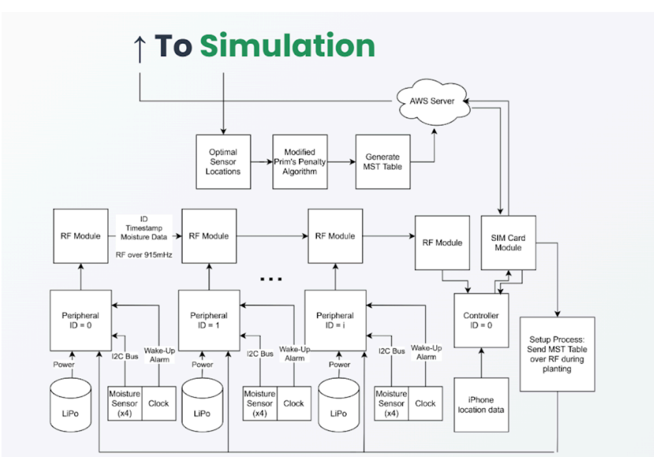

Figure 3: Hardware Block Diagram

D. Mathematical Modeling

The AgriFlow system integrates the open-source KINEROS2[1] hydrological model to simulate runoff and estimate post-rain nutrient loss across sloped agricultural fields. Rather than developing a custom simulation engine from scratch, we adopted KINEROS2[1] due to its robust, physically based framework and proven applicability in distributed watershed modeling. Developed by the USDA Agricultural Research Service, KINEROS2[1] is an event-oriented, one-dimensional, physically based model capable of simulating interception, infiltration, surface runoff, and sediment transport over complex terrain.

The model represents watersheds as a cascade of interconnected overland flow planes and channels, solving the governing kinematic wave equations using finite difference techniques. This structure makes it particularly well-suited to our use case, where runoff behavior is heavily influenced by field slope, spatial variability in rainfall, and soil characteristics. KINEROS2[1] accounts for interactions between rainfall, soil infiltration, and surface water transport, and supports dynamic redistribution of soil water during rainfall interruptions—features that are essential for accurately estimating nitrogen loss following storm events.

In our implementation, KINEROS2 is integrated into the AgriFlow data pipeline, with field-specific inputs automatically generated from sensor data, digital terrain models, and real-time weather forecasts. Sensor data collected from the distributed peripheral devices—including volumetric soil moisture and slope orientation—is pre-processed in the cloud and formatted to match the spatial structure required by KINEROS2. Each field is partitioned into flow elements, and parameters such as hydraulic conductivity, soil depth, and slope are populated from both sensor readings and geospatial datasets.

III. Implementation

The implementation phase translated the AgriFlow system design into functional hardware and software components. This section outlines the practical realization of the peripheral sensor nodes, the master device, enclosure design, and software infrastructure, highlighting key engineering decisions and integration strategies.

A. Hardware Implementation

The AgriFlow peripheral nodes were developed on custom PCBs designed in Altium, supporting up to 16 capacitive moisture sensors through I²C communication through an ADS1115. Each node typically operates with six moisture sensors, although the design is flexible to accommodate varying use cases. The core processing unit is the nRF52840 microcontroller, selected for its ultra-low power consumption and robust RF capabilities. To manage scheduled wake ups from deep sleep, each peripheral includes a MAX31329ELB+ real-time, ultra energy efficient clock, which serves as the timing controller for daily transmissions. The primary communication component is the RFM69HCW radio module, operating at 950 MHz. As the most energy-intensive element in the system, its usage is carefully constrained to a single transmission window per day that can operate for a maximum of 30-seconds.

Power is supplied by a 3.7V, 3000 mAh Li-Po battery, chosen to meet the long-term deployment requirement of over seven years. The peripheral also includes a push-button and status LED to facilitate pairing and setup in the field. The schematic of the peripheral with all the necessary components and its corresponding PCB is seen in Figures 4 and 5 below.

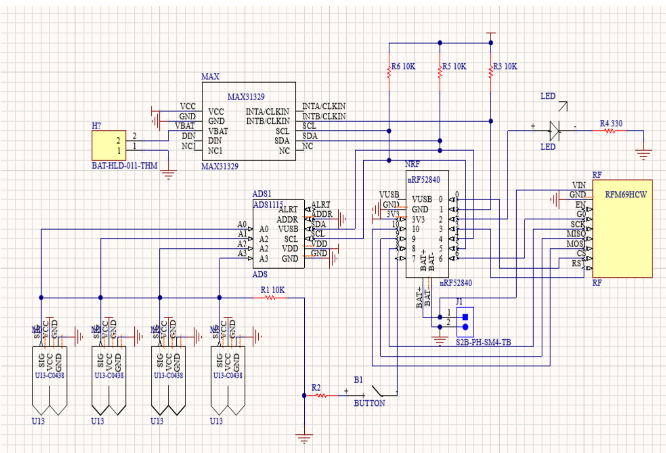

Figure 4: Peripheral Schematic with Four Sensors

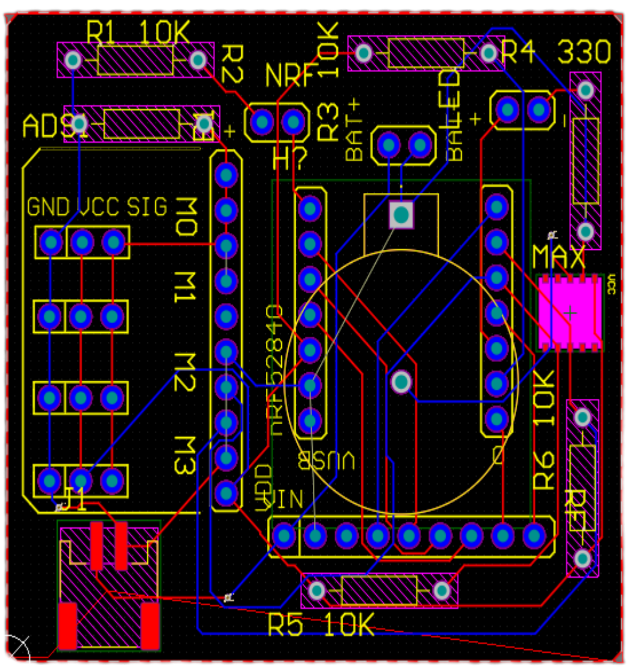

Figure 5: Peripheral PCB

The master device is powered through a standard AC connection, typically installed in a barn or on-site utility structure. It is built around the ESP32-Feather microcontroller, which interfaces with a Waveshare SIM7600G-H 4G module to transmit data to the cloud. During the setup process, the master is temporarily powered by an onboard 3000 mAh battery, allowing it to be moved to various peripheral locations without reliance on fixed infrastructure.

The pairing process is initiated by pressing the synchronization button on the peripheral. The master device then identifies the active peripheral in setup mode through an RF setup handshake, and retrieves a device-specific communication table from the cloud—including the location of the setup user, which gets polled from the setup user's phone's built-in GPS at setup, capturing the peripheral device's location. The communication table defines the RF mesh structure by specifying the node's position in the minimum spanning tree (MST). The master then transmits the relevant routing configuration through a query to the server via the SIM7600G-H 4G module to the peripheral through RF, which stores the information locally for subsequent synchronized communication.

Peripheral enclosures are designed to be weatherproof and support long-term durability in diverse field conditions. The modular mechanical design allows for in-field assembly and enables users to install moisture sensors at varying depths, depending on soil type and agronomic requirements. This modularity simplifies deployment and enhances adaptability across different farm environments.

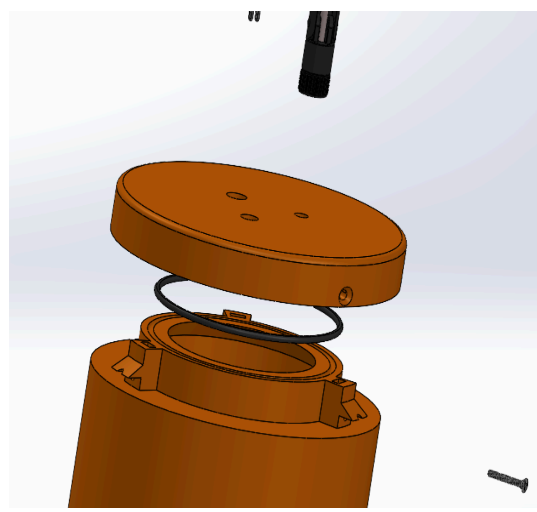

Figure 6: Sealed O-Ring Waterproof Configuration

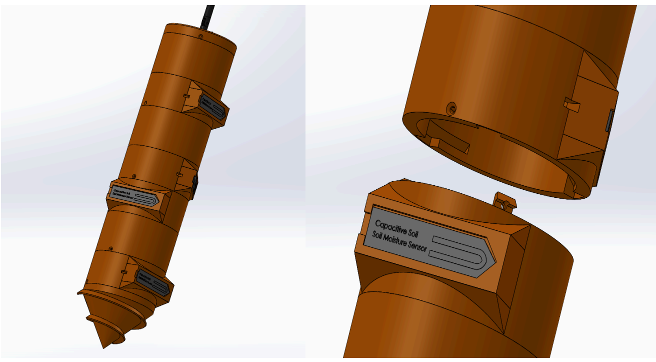

Figure 7: Mechanical Peripheral Modularity

The Modular Mechanical Design as seen in Figure 7 allows for the on-site assembly of peripheral devices and the placement of different capacitance soil moisture sensors for varying heights and soil content based on the farmer's needs.

B. Software Implementation

Figure 8: Elevation Profile Generation (Frontend)

The AgriFlow software stack consists of three integrated layers: frontend, simulation backend, and cloud infrastructure. The frontend is built using the MERN stack (MongoDB, Express, React, Node.js), providing an intuitive web application for farmers to visualize sensor placements, select farm plots, and access nutrient runoff predictions. Google Maps integration enables high-resolution geospatial visualization[3], allowing for sub-meter precision in field mapping and device management.

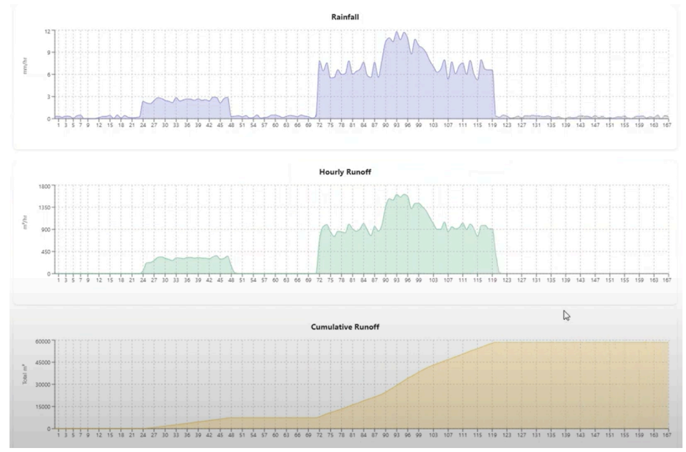

Figure 9: Runoff Simulation (Frontend)

The backend runs on AWS and is responsible for aggregating data from the master device, storing sensor readings, rainfall forecasts, and user configurations in a MongoDB Atlas database. The backend also manages the generation of the RF mesh communication structure by constructing a minimum spanning tree (MST) generated from a modified Prim's node proximity and hop penalty algorithm. This algorithm minimizes the number of transmissions and ensures energy-efficient communication between peripherals and the master, for example seen in Figure 10.

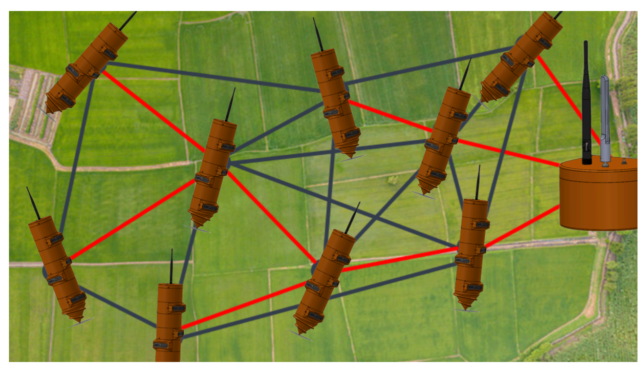

Figure 10: Modified Prim's Hop Penalty Algorithm Result

Each peripheral node is assigned a unique hash table during setup, defining its data transmission role within the network. The structure of the routing table is as follows:

```
struct PeripheralLookupTable {
        // This peripheral's ID
  char peripheral[MAX_ID_LENGTH];
        // Number of incoming nodes
  uint8_t numIncoming;
        // Number of outgoing nodes
  uint8_t numOutgoing;
        // List of upstream nodes
  char incoming[MAX_NODES][MAX_ID_LENGTH];
        // List of downstream nodes
  char outgoing[MAX_NODES][MAX_ID_LENGTH];
};
```

Upon wakeup, each node listens for data from its defined upstream (incoming) nodes. If no upstream nodes are present, the node transmits immediately. This hierarchical data flow causes the most remote nodes to initiate transmission, because they have no incoming nodes in their peripheral lookup table with subsequent nodes aggregating and relaying data until it reaches the master. The master then uploads the complete dataset to the cloud via the cellular module.

The simulation module operates server-side, executing KINEROS2-based runoff predictions using the ingested sensor data and rainfall inputs. The outputs are updated and displayed on the frontend.

IV. Testing and Verification

To validate the performance of the AgriFlow system, a series of controlled and field-based tests were conducted to evaluate sensor calibration, energy consumption, communication range, and simulation accuracy. These experiments confirm that the system meets the design requirements outlined in Section II.

A. Greenhouse Trials

Sensor calibration was conducted in collaboration with the Penn Biology Department Greenhouse to ensure reliable measurement of Gravimetric Water Content (GWC). Capacitive soil moisture sensors were tested across various soil conditions and compared against known gravimetric values. The results demonstrated consistent linear behavior, yielding a sensor accuracy of ±2%.

Figure 11: Example Greenhouse Setup With Capacitance Soil Sensors on Custom Built Testing Hardware

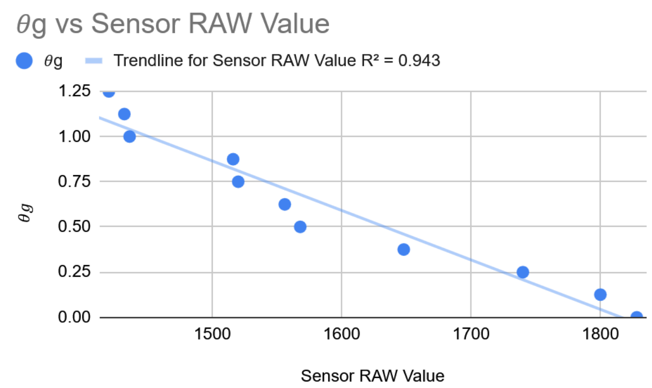

Figure 12: Calibration Results

A linear calibration equation was derived from these tests:

$\theta g = -0.00274 \times \text{Sensor Raw Value} + 4.97$

where θg is the gravimetric water content. For accurate and repeatable conversion, it was necessary to standardize soil type and ensure full submersion of the sensors during data collection, or alternatively calibrate for partial submersion. These calibration parameters are now applied across all peripheral devices to convert raw sensor readings into meaningful agronomic metrics.

B. Energy Consumption Tests and Verification

To verify long-term viability in the field, energy consumption tests were conducted on the full nRF52840-based peripheral devices. The current draw of each major component was calculated under both transmission and deep-sleep modes. The results of said calculations can be found in Table 1 and 2.

	RFM69HCW (mA)	nRF52840 + Other Components (mA)	MAX31329ELB (mA)
Transmission	130	16.2	0.2
Deep-sleep	0.0001	0.0009	0.0007

Table 1: Calculated Current Expenditure of Peripherals and It's Critical Components

	Total (mA)	Minutes ON / day	mAh / day	mAh/year
Transmission	146.4	0.5	1.22	445.30
Deep-sleep	0.0017	1439.5	0.04	14.89

Table 2: Total mAh Calculations of Full Peripheral

Under worst-case conditions - assuming maximum power transmission at 20 dB for the entire 30-second window—the system would draw approximately 460.19 mAh/year. This corresponds to a theoretical battery life of 6.52 years on a 3000 mAh battery and 10.87 years on a 5000 mAh battery, meeting the goal of > 7 years in real-world deployments.

To further refine our energy consumption estimates, we conducted empirical tests replicating the actual operating conditions of the peripheral device. These tests involved executing the iterative sending protocol, where the device transmits four RF packets during its 30-second active window between deep sleep cycles. As shown in Figure 13, distinct current spikes are visible at transmission intervals, corresponding to packet dispatch through RF. The duration of active transmission was measured at approximately 5.125 seconds, significantly shorter than the full wake period, illustrating the efficiency of the communication schedule.

Figure 13: Empirical Measurements of Current Through Active RF Transmissions on The Peripheral Hardware

Even when the RFM69 module is configured to transmit at its maximum output power of 20 dB, the peak current draw observed was 124.42 mA—below the initially projected 130 mA threshold. The average current draw across the entire transmission period was calculated at 21.27 mA, confirming the feasibility of low-power, high-reliability RF communication under typical deployment conditions.

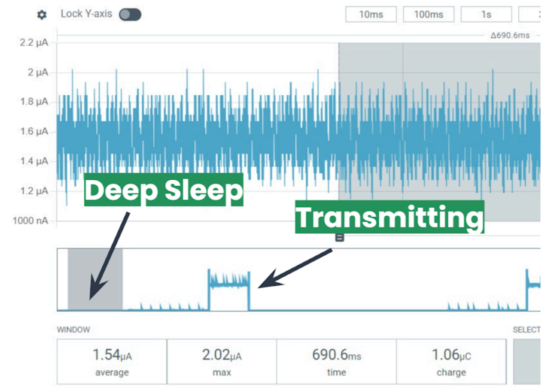

Figure 14: Empirical Energy Measurements of The Peripheral Transitioning Between Deep Sleep and Transmitting

In deep sleep mode, as illustrated in Figure 15, the system was designed to exhibit extremely low power draw. This figure captures alternating sleep and wake cycles, and demonstrates a consistent average current of 1.54 µA. At this stage, all system components are disabled except the nRF52840 microcontroller in ultra-low power mode and the MAX31329ELB+ real-time clock, which maintains timing for scheduled wake-ups. This performance validates the deep-sleep functionality required for multi-year operation, with said empirical measurements seen in Table 3.

	Empirical Tests Average (mA)	Minutes ON / day	mAh / day	mAh/year
Transmission	21.27	0.5	0.18	64.70
Deep-sleep	0.00154	1439.5	0.04	13.49

Table 3: Empirically Tested Current Expenditure of Peripherals and It's Critical Components

Based on these empirical measurements, the projected daily energy consumption of the device is 0.18 mAh for transmission and 0.04 mAh for deep sleep. These values yield a total annual consumption of approximately 78.19 mAh, as summarized in Table IV.2. This translates to a theoretical battery life exceeding 10 years when powered by a 3000 mAh LiPo battery, thus surpassing the original design target of seven years. In contrast, the master device is powered via a stable AC power source—typically in a barn or utility building—and does not face the same energy constraints. During normal operation, it remains continuously active to receive data from peripheral nodes and transmit it to the cloud via the onboard SIM7600G-H 4G communication module.

In the rare case where setup occurs in the field without immediate AC access, the master device switches to a 3000 mAh internal battery. This temporary power supply is sufficient for the limited demands of setup, which include low-power RF synchronization signals and occasional high-power SIM transmissions. As such, battery endurance is not a significant concern for the master unit.

To ensure continued time synchronization, each MAX31329ELB+ clock module within the peripheral is equipped with a dedicated 3V coin-cell battery that functions as a backup power source. Given that the nRF52840 gets awoken through a GPIO pin set by the clock module, this backup ensures that the MAX31329ELB+ never falters even in the event of a temporary battery disconnection. By preserving time data through the clock's internal registers, the device avoids wakeup failures and maintains network integrity. The only other known edge case for potential timing drift is corrected during data transmission, where each peripheral reports its internal clock value back to the master, enabling periodic recalibration of timing across the network.

C. Field Testing

Field testing was conducted to evaluate the reliability of the wireless communication network and verify full system functionality under real-world deployment conditions. Peripheral devices were distributed across open outdoor test plots to assess the effective range of RF communication between nodes. Results confirmed consistent and stable transmission at distances up to 200 meters—satisfying the system's design requirement whereby peripheral devices are placed 200 meters adjacent to each other.

Additionally, integration tests of the master device were performed to validate end-to-end data flow from sensors to the cloud. The ESP32-based master node successfully received data from the RF mesh network and transmitted it to the AWS-hosted backend using the SIM7600G-H 4G communication module. Data uploads were confirmed via the AgriFlow web interface, demonstrating that the entire system—from sensor acquisition to cloud visualization—is operational, reliable, and ready for field deployment.

V. Applicable Standards

In the development of AgriFlow, several industry and international standards were considered to guide decisions around communication protocols, geospatial data handling, environmental responsibility, hardware design, and data security.

IEEE 802.15.4 was referenced for its principles around low-power, short-range wireless communication, which informed the selection and configuration of our RF modules.

ISO 19115 helped shape our approach to organizing geospatial metadata, ensuring compatibility with common mapping and GIS frameworks.

ISO/IEC 27001 informed general best practices around securing user data and cloud communication, particularly in managing sensitive agricultural and location-based information.

ISO 14001 was considered in the broader environmental objectives of the project, particularly in addressing fertilizer runoff and sustainability.

IPC-2221 provided general guidelines for robust PCB layout and design, which were referenced during hardware prototyping.

Although AgriFlow has not been formally certified under any of these standards, they served as reference points to promote scalable, responsible, and interoperable system design.

VI. Ethical Considerations

The AgriFlow project considered several ethical aspects during its development, including responsible data handling, fairness in technology access, and transparency in decision-making tools. Efforts were made to respect user data, avoid unnecessary electronic waste, and ensure that the technology serves farmers without introducing undue dependence or inequality. While not all ethical challenges can be fully addressed at this stage, they remain important considerations as the system evolves.

VIII. Environmental, Social, Economic Impact.

AgriFlow has the potential to generate significant positive environmental, social, and economic outcomes. By optimizing fertilizer application and reducing nutrient runoff, the system helps protect waterways and surrounding ecosystems from harmful chemical exposure. Excess fertilizers are a major contributor to environmental degradation, including algal blooms, the spread of invasive species, and the decline of aquatic biodiversity. By mitigating these effects, AgriFlow supports healthier habitats and more sustainable land use practices. Socially, the platform empowers farmers with data-driven tools to make informed decisions, improving resource efficiency and promoting environmentally responsible agriculture. Economically, reducing fertilizer waste lowers input costs and enhances long-term soil health, contributing to more resilient and profitable farming operations.

VIII. Conclusions and Reflections

Agriflow's design successfully integrates hardware, software, and simulation models to provide actionable insights for farmers. Testing in both greenhouse and field environments confirms robust hardware reliability and communication integrity. The system is on track for scaling and large-farm deployment. Future work will focus on refining 2D modeling capabilities and exploring machine learning integration for predictive accuracy improvements.

X. Business Writeup

A. Executive Summary

Agriflow is a pioneering enterprise dedicated to transforming agriculture by providing farmers with real-time insights to optimize fertilizer usage, reduce environmental impact, and minimize financial losses from nitrogen runoff. Traditional farming practices result in approximately 65% of fertilizers being lost to ecosystems[2], leading to $75 billion in annual losses and contributing over 2.6 billion tons of CO_2 emissions worldwide.

Agriflow addresses these challenges through an integrated platform that combines advanced IoT soil moisture sensors, precise terrain mapping, and predictive runoff simulation models. This solution provides real-time data and actionable insights, enabling farmers to make informed, data-driven decisions that enhance fertilization precision, reduce costs, and promote sustainable practices. Our focus on large-scale farms, which manage around 40% of global agricultural land, positions Agriflow to meet the increasing demand for scalable and cost-effective agricultural technologies driven by rising fertilizer costs and market consolidation.

By automating soil monitoring and delivering continuous, real-time data, Agriflow eliminates the need for traditional soil testing and complements existing satellite data solutions. With a strong value proposition, strategic market focus, and a commitment to sustainability, Agriflow is well-positioned to lead the precision agriculture market, delivering significant economic and ecological benefits to farmers globally.

B. Value Proposition

Agriflow offers a targeted, data-driven solution for large-scale farms managing sloped terrain, where rainfall-induced nutrient runoff undermines conventional soil testing. By integrating custom-built, long-lifetime moisture sensors with high-resolution elevation mapping and the KINEROS2[1] runoff simulation engine, Agriflow delivers post-storm nitrogen loss estimates that inform precise fertilizer reapplication. This combined hardware-software platform addresses a critical blind spot in current precision agriculture practices, enabling farmers to reduce input waste, improve yield efficiency, and minimize environmental impact—while maintaining compatibility with existing agronomic workflows.

C. Stakeholders

Large-scale farmers with sloped terrain – seeking tools to optimize fertilizer use and reduce yield uncertainty following rainfall events.

Agronomic consultants and service providers – interested in integrating predictive runoff data into broader crop management strategies.

Environmental and regulatory bodies – focused on curbing agricultural runoff and nitrogen pollution through precision intervention.

Agritech distributors and cooperatives – positioned to scale deployment through existing relationships and infrastructure.

University researchers and extension programs – supporting validation efforts and advancing adoption through field trials.

Precision agriculture platform integrators – aiming to enhance existing tools with advanced runoff modeling capabilities.

D. Market Research

Market research suggests that roughly 1% of U.S. cropland consists of steep-sloped fields vulnerable to nutrient runoff, translating to approximately 5.87 million acres. Within this subset, large-scale farms—defined as those managing over 1,000 acres—represent the most viable customer base, particularly given their higher fertilizer usage and increasing adoption of precision agriculture tools. Industry data indicates that only a fraction of these operations currently employ moisture sensors or runoff-aware decision tools, highlighting a clear gap in the market. While existing products provide general soil moisture data, they fail to account for nitrogen displacement caused by storm events. Agriflow addresses this unmet need by combining predictive runoff modeling with durable, field-tested hardware, positioning itself as a differentiated solution in a growing segment of precision agriculture.

E. Target Customer Segment and Market Opportunity

Agriflow's target customer segment consists of large-scale farms in the United States managing over 1,000 acres, with a specific focus on those operating on sloped terrain prone to rainfall-driven nutrient runoff. These operations typically have higher input costs, greater sensitivity to yield variability, and an existing familiarity with precision agriculture technologies, making them well-positioned to adopt advanced sensor networks and data-driven decision tools. Within this group, early adopters are likely to be growers already using soil moisture sensors or working with agronomic consultants who can integrate runoff insights into broader nutrient management strategies.

Our target customers are large-scale farms with more than 1,000 acres of land, which collectively account for 587 million acres in the United States. We estimate that approximately 1% of this land — or 5.87 million acres — consists of fields with steep slopes that are especially vulnerable to runoff. Focusing on this niche allows us to solve a highly specific but economically significant problem. Of these 5.87 million acres, roughly two-thirds already use precision agriculture tools, yielding an obtainable market of 3.9 million acres. At our current price point of $200 per sensor per year, this represents a potential revenue opportunity of $78 million. This market sizing supports our decision to focus on a technically sophisticated but operationally simple solution aimed at high-value acreage.

F. Competition

Agriflow enters a competitive landscape populated by firms such as SoilSense, Soiltech Wireless, Spiio, and EarthScout—all of which offer moisture sensing solutions with varying levels of hardware sophistication and software integration. Most competitors focus exclusively on soil moisture monitoring, delivering data through cloud-connected platforms with annual subscription models. For example, Soiltech offers devices at around $500 with ongoing service fees, while EarthScout's high-end solutions exceed $1,800 per unit but include five years of data service. In contrast, Agriflow differentiates itself by integrating real-time moisture data with a validated runoff simulation engine (KINEROS2), offering not just sensing but predictive agronomic insight. Combined with long-lifetime, modular hardware designed for harsh field conditions, Agriflow delivers a more actionable and cost-efficient solution for farms facing runoff-related fertilizer inefficiencies.

G. Cost

Our current cost structure includes four primary categories: hardware manufacturing, setup and installation, maintenance, and support services. Of these, maintenance — especially emergency fixes — accounts for the largest and most unpredictable portion. High costs are typically incurred when RF communication fails or when batteries deplete faster than expected, requiring urgent on-site repairs. These issues introduce costs that significantly affect our gross margin. That said, even with these challenges, our pricing strategy still allows for a projected gross margin of 70%. To improve cost efficiency, we are investing in better RF reliability and longer-lasting battery solutions, which will reduce unplanned interventions and enhance long-term profitability.

H. Revenue Model

Agriflow's revenue model is simple and recurring: $200 per sensor per year. For a typical deployment on a 1,000-acre farm—using one sensor per 10 acres—this translates to 100 sensors and $20,000 in annual revenue. This model aligns with existing precision agriculture spending patterns and enables predictable, subscription-based cash flow. Over time, the platform may offer additional revenue opportunities through premium analytics, API integrations, or extended service contracts, but the initial focus is on maximizing adoption by offering competitive pricing without charging extra for the runoff simulation engine.

I. IP

Agriflow's intellectual property lies in the integration of proprietary hardware architecture with a custom RF communication protocol and a predictive runoff modeling pipeline tailored for sloped agricultural terrain. The hardware includes custom-designed PCBs, modular waterproof casings, and ultra-low-power firmware that enables synchronized sensor wake-up and data relay using a modified Prim's algorithm for network optimization. While core components such as the KINEROS2[1] model and Google Maps API[3] are open-source or third-party, the system's novel configuration—linking geospatial terrain data, field-deployed sensors, and nitrogen loss simulation into a unified decision tool—represents protectable design and system-level IP, particularly in how timing, pairing, and data transmission are coordinated across the sensor network.

J. Pilot Deployment

To address the current data limitations and demonstrate product value in a real-world setting, we plan to launch a pilot in Virginia's Shenandoah Valley — a region characterized by steep-sloped terrain and high susceptibility to agricultural runoff. The pilot will target 10 to 25 high-slope fields where runoff significantly impacts fertilizer efficiency and crop health. By offering our runoff model at no cost during this phase, we aim to reduce the barrier to entry for farmers, encourage usage, and capture detailed sensor data. This pilot will allow us to measure real-world impact, gather testimonials, and calibrate the model for broader deployment. The end goal is to build the empirical case for future value-based pricing and market expansion.

K. Next Steps

Before we move into full-scale commercialization, we plan to continue refining the performance, usability, and robustness of our system. This will involve ongoing testing in collaboration with IoT4Ag and other partners to stress-test our sensors under varying environmental conditions. In parallel, we will broaden our outreach to farmers across different regions to collect feedback, validate our business model, and confirm compliance with agricultural regulations. These steps are essential to de-risk the scaling process, fine-tune our value proposition, and solidify our go-to-market strategy. The learnings from this pre-market phase will directly inform improvements to both our hardware and software platforms.

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Biography

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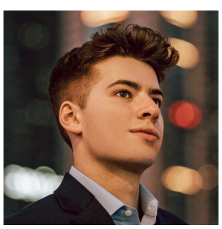

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