Simulating Drip Irrigation (DI) System For Optimizing Water Use Efficiency

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***Abstract*—Drip irrigation is a water-efficient method for crop production, particularly in water-scarce regions. The Drip Irrigation System Simulation is a tool designed to model the performance of drip irrigation systems under varying weather conditions and soil moisture levels. The simulation helps users understand irrigation requirements, system efficiency, and water usage over a specified period. The simulation includes features for simulating daily weather conditions and soil moisture levels, calculating irrigation requirements based on crop water requirements and soil moisture deficit, computing total system flow rate and pressure loss, and visualizing key metrics such as soil moisture, water usage, rainfall, evapotranspiration, and more. The simulation can be used to assess irrigation requirements, optimize system efficiency, and understand water usage patterns. It is a valuable tool for farmers, agricultural engineers, and researchers who are interested in improving irrigation management practices.**

***Index Terms*—Drip irrigation, Simulation, Water efficiency, Irrigation Requirements, System efficiency, water usage.**

I. Introduction

Drip irrigation techniques are a promising solution to water scarcity and environmental concerns in agriculture. Drip irrigation, a method that delivers water directly to the root zone of crops through a network of pipes and emitters, has garnered significant attention due to its remarkable ability to minimize water loss compared to traditional irrigation methods like furrow irrigation. The Drip Irrigation System Simulation (DISS) stands as empowering users with a comprehensive tool for understanding, optimizing, and managing drip irrigation systems.

DISS is carefully designed to model the performance of drip irrigation systems under a dynamic range of weather conditions and soil moisture levels. It equips users with invaluable insights into irrigation requirements, system efficiency, and water usage patterns, enabling them to make informed decisions that transform irrigation management practices. The simulation incorporates a suite of sophisticated features that encompass simulating daily weather conditions and soil moisture levels, calculating irrigation requirements based on crop water requirements and soil moisture deficit, computing total system flow rate and pressure loss, and visualizing key metrics such as soil moisture, water usage, rainfall, evapotranspiration, and more.

DISS empowers farmers, engineers, and researchers to gain valuable insights into their drip irrigation systems. This knowledge empowers them to optimize irrigation schedules, enhance system efficiency, and conserve precious water resources, thereby contributing to the preservation of our planet's finite water reserves. Moreover, DISS serves as an invaluable tool for evaluating the impact of different irrigation system designs and management practices on crop productivity and water use efficiency, paving the way for informed decisions that maximize crop yields while minimizing water usage.

The significance of DISS is that it holds immense significance in addressing the critical challenges faced in agricultural water management:

- Combating Water Scarcity: DISS provides a means to minimize water loss and maximize water use efficiency in drip irrigation systems, effectively combating water scarcity and ensuring sustainable water usage in agriculture.
- Promoting Sustainability: DISS fosters sustainable agricultural practices by reducing reliance on conventional irrigation methods that contribute to water depletion and environmental degradation.

- Enhancing Crop Productivity: DISS empowers users to tailor irrigation schedules to meet the specific water requirements of different crops, fostering optimal growth conditions and enhancing crop productivity and yield.
- Achieving Economic Efficiency: DISS contributes to cost-effective irrigation management by optimizing water usage and minimizing water losses, reducing irrigation expenses and maximizing economic returns.

The applications of DISS are many. DISS finds application in a diverse range of agricultural scenarios:

- Irrigation System Design: DISS can be employed to evaluate and optimize the design of drip irrigation systems, ensuring adequate water delivery and minimizing pressure losses, leading to efficient and effective irrigation systems.
- Irrigation Scheduling: DISS empowers farmers to determine optimal irrigation schedules based on crop water requirements, soil moisture levels, and weather conditions, ensuring timely and precise water application.

II. Related Work

In paper [1] researchers developed irrigation optimization models for citrus orchards in seasonal arid regions using four years of field data. They established six scenarios with varying water availability and employed an optimization algorithm to identify the best irrigation strategies. The study found that the Minhas water-yield model and Q-Rao water-fruit quality model were the most accurate. The optimization model successfully identified irrigation strategies that improve fruit quality and water use efficiency. The optimal water allocation strategy varies depending on water availability. The study's findings provide valuable insights for water management strategies in citrus orchards in seasonal arid regions and can help farmers tailor irrigation schedules to specific conditions.

Emmanuel Abiodun Abioye et al. (2021) developed an IoT-based drip irrigation system to precisely monitor and control water usage during mustard leaf cultivation in [2]. The system utilized sensors to collect data on soil moisture content, reference evapotranspiration, and irrigation volume. A data-driven modeling approach was employed to establish a predictive model that mimics the dynamics of the irrigation system. The model effectively predicted the irrigation water requirement for mustard leaf cultivation based on real-time sensor data. The IoT-based monitoring system enabled real-time visualization of soil moisture content and irrigation volume, facilitating optimal water management. The data-driven modeling approach provided a valuable tool for predicting future irrigation needs and optimizing water usage efficiency. The implementation of the IoT-based drip irrigation system and data-driven modeling approach demonstrated the potential for drip irrigation in mustard leaf cultivation. The study's findings contribute to the development of sustainable and efficient irrigation practices for mustard leaf production.

The authors in [3] developed a co-simulation virtual reality (VR) machinery simulator to enhance Drip agriculture practices. The simulator incorporates a physical tractor cab mounted on a motion base, a high-definition screen, and a sound system. It utilizes nine computers running open-source software to simulate various driving scenarios and implement drip agriculture operations. The VR environment allows researchers and farmers to evaluate the effectiveness of different machinery configurations and drip agriculture techniques without risking physical harm or damage to equipment. This simulator has the potential to revolutionize agricultural training and research, enabling the development of more efficient and sustainable farming practices.

This paper [4] delves into the design and implementation of an agriculture monitoring system using Arduino, an open-source microcontroller board, and Android-based smartphones. The system aims to provide real-time data on soil moisture, temperature, and humidity, enabling farmers to make informed irrigation decisions and optimize crop yields. The Arduino board serves as the data acquisition unit, while the Android app facilitates data visualization and remote monitoring capabilities. The study highlights the effectiveness of the proposed system in enhancing agricultural practices and promoting sustainable water management.

A study comparing the efficiency of drip irrigation (DI) and border irrigation (BI) for corn cultivation found that DI significantly outperforms BI in both water-use efficiency (WUE) and nitrogen-use efficiency (NUE) in [5]. Over a four-year period, DI increased WUE by 28 percent and NUE by 39 percent compared to BI. These improvements are attributed to DI's precise water and nutrient delivery, which minimizes losses and optimizes utilization for crop requirements. The findings suggest that DI is a more sustainable and resource-efficient irrigation method for corn production, particularly in water-scarce regions.

The Cognitive Distributed Computing System (CDCS) for Intelligent Agriculture is a novel approach that is introduced in [6] to Drip agriculture that utilizes distributed computing, cognitive computing, artificial intelligence, and the internet of things (IoT) to address the challenges faced by traditional agriculture. It aims to improve water and fertilizer usage, pest and disease control, and real-time crop health monitoring and analysis. CDCS leverages the power of distributed computing to collect, process, and analyze large volumes of agricultural data from various sources, including sensors, satellites, and drones. This data is then fed into cognitive computing algorithms to extract meaningful insights and patterns, enabling farmers to make informed decisions about their crops. CDCS also utilizes artificial intelligence techniques to develop predictive models that can anticipate crop growth, potential pests and diseases, and market trends. These models empower farmers to optimize their farming practices, maximize yields, and minimize risks. IoT plays a crucial role in CDCS by providing real-time data on various environmental factors, such as temperature, humidity, soil moisture, and light intensity. This real-time data enables farmers to continuously monitor their crops and make timely interventions when necessary.

The paper [7] explores the role of cloud and distributed architectures in managing the vast amounts of data generated by Agriculture 4.0 practices. It delves into various cloud and distributed architectures, including central cloud, distributed cloud, and collaborative computing strategies, and analyzes their suitability for different data management scenarios in Agriculture 4.0. The paper also highlights emerging trends in data management, such as edge computing, fog computing, and blockchain technology, and discusses their potential impact on the future of data management in Agriculture 4.0.

This paper [8] proposes a drip agriculture design method that utilizes a distributed computing architecture within an Internet of Things (IoT) context. The method aims to gather, store, process, and analyze large volumes of agricultural data generated from a variety of IoT devices, including sensors, drones, and satellites. By employing this data, farmers can optimize irrigation, fertilization, and pest control practices, leading to increased crop yields and reduced environmental impact. The proposed method comprises four main components: a data acquisition layer responsible for collecting data from IoT devices and transmitting it to the data processing layer; a data processing layer responsible for cleaning, preparing, and storing the data in a distributed database; an application layer responsible for analyzing the data and providing decision support to farmers; and a presentation layer responsible for displaying the data and providing recommendations to farmers. The implementation of this method in a citrus orchard in Spain has demonstrated its effectiveness in improving irrigation efficiency, reducing water consumption, and increasing crop yields. This method holds promise for revolutionizing drip agriculture practices, enhancing productivity, and fostering sustainability in agricultural endeavors.

Drip irrigation is an efficient and sustainable approach to crop production in water-scarce regions like Northwest China. A study [9] by Jia et al. (2015) evaluated the impact of drip irrigation on maize cultivation in this region. The researchers tested three irrigation treatments: traditional furrow irrigation, single-line drip irrigation, and double-line drip irrigation. The results showed that drip irrigation significantly improved water use efficiency (WUE) compared to traditional furrow irrigation. Double-line drip irrigation achieved the highest WUE, a 26.9 percent increase over furrow irrigation. Drip irrigation systems apply water directly to the crop root zone, minimizing evaporation and deep percolation losses. This precise water application, along with uniform soil moisture distribution, contributes to increased maize biomass and grain yields. The study's findings highlight the advantages of drip irrigation for maize cultivation in Northwest China. Drip irrigation offers a sustainable solution for water management, promoting crop productivity while conserving precious water resources.

III. Methodology

A. Description of the Simulation Model

The study simulates a drip irrigation system using a computational model developed in Python. The purpose of this model is to assess the water consumption efficiency of the system under some discrete input parameters, weather and soil condition data and performed calculations over the data points as shown in Figure1. Several Python libraries are used in this model; such as; NumPy is utilized for numerical calculations, pandas for data handling and manipulation, and matplotlib for visualizing the results.

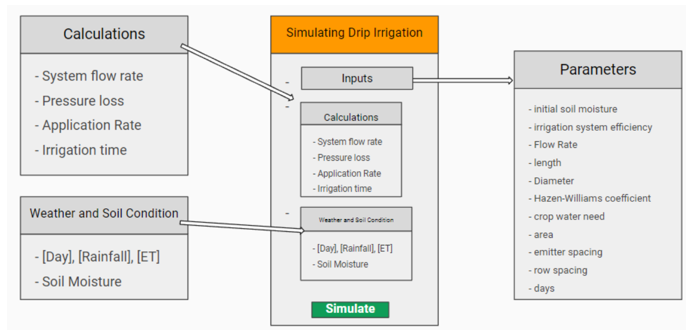


Fig. 1: Simulation Model

B. Input Variables and Parameters

As shown in Figure1, the Inputs section represents the data or variables or parameters that are entered into the simulation. These input variables could be user-defined or derived from measurements and observations such as: flow rates for each emitter, the dimensions of the irrigation system, and initial conditions like soil moisture levels. And the parameters are fixed settings and configurations within which the simulation operates, are generally not changed during a single simulation run (like length and diameter of pipes), and environmental factors like crop water need and area covered.

C. Data Collection and Calculation

1) System Flow Rate: The model generates flow Rates (FR) for each emitter using a uniform distribution between 0.5 and 1.0 gallons per hour (GPH), reflecting the variability in emitter output.

$$\text{Total Flow Rate} = \sum \text{Flow Rate per Emitter} \qquad (1)$$

2) Pressure loss and Specifications: The simulation incorporates fixed parameters such as the length of the irrigation line (200 feet), the diameter of the line (0.75 inches), and the Hazen-Williams coefficient (C, set at 140), crucial for calculating the pressure loss (PL) in the system. Here Hazen-Williams coefficient is set at 140. This indicates a relatively smooth pipe, allowing for efficient water flow with minimal pressure loss.

$$\mathrm{PL} = 10.67 \times \mathrm{L} \times \left(\frac{\mathrm{FR}}{448.831}\right)^{1.852} \div \left(C^{1.852} \times \mathrm{D}^{4.87}\right) \qquad (2)$$

3) Crop Water Need and Area Coverage: The model considers a crop water need of 1.0 inch per week and an area of 1000 square feet. These parameters are integral to determining the overall water requirement for the area.

4) Application Rate: Emitter and row spacings are set at 1 foot each, which are used in calculating the water application rate.

$$\text{Application Rate} = \frac{\text{Emitter Flow Rate} \times 231}{\text{Emitter Spacing} \times \text{Row Spacing}} \quad (3)$$

D. Weather and Soil Condition

In our study, the process encompasses creating a model that closely represents the daily changes in soil moisture due to environmental factors and calculates the need for irrigation based on these changes. The simulation begins by creating a data frame to hold the daily weather data, which includes simulated values for rainfall and evapotranspiration (ET0). These values are generated randomly to represent the variability in daily weather conditions. Alongside this, two lists are initialized: one to track soil moisture and another for daily water usage. Then the process begins as shown in Figure 2, alongside the arrays or lists tracking soil moisture and water usage, proceeding to calculate the net change in soil moisture for each day, accounting for input from rainfall and output due to ETO, which influences the soil's water content.

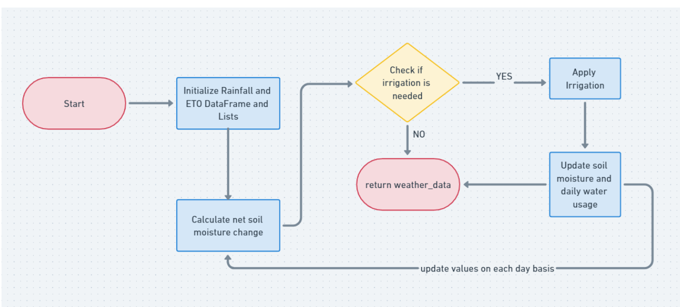


Fig. 2: Storing Weather and Soil data

As the simulation advances, it evaluates whether the adjusted soil moisture level falls below the crop's water requirement threshold, indicating the need for irrigation. If irrigation is necessary, the system simulates the application of water, subsequently updating the soil moisture and water usage logs. In the absence of such a need, the simulation merely updates these logs without any irrigation event. This daily iterative process continues, outputting the compiled weather data which includes the day's rainfall, ETO, updated soil moisture, and the day's water usage, thereby enabling a dynamic response to fluctuating environmental conditions. At the end of each day's simulation, the updated weather data, including the day's rainfall, ETO, soil moisture, and water usage, is outputted, ready to be used for the next day's calculations or for analysis after the simulation run is complete.

E. Analytical Techniques

1) Simulation Execution: The simulation runs over a 10-day period, with each day's data including soil moisture levels, water usage, and irrigation requirements.

2) Data Analysis: Key performance metrics analyzed include total system flow rate, pressure drop across the system, and the application rate of water to the crops. The model also evaluates daily water usage and soil moisture levels.

IV. Simulation Setup

A. System Configuration

The drip irrigation system in the simulation is configured with specific parameters to mimic real-world conditions. The system consists of multiple emitters with flow rates randomly assigned between 0.5 and 1.0 gallons per hour (GPH). The total length of the irrigation line is set at 200 feet, with a diameter of 0.75 inches. The Hazen-Williams coefficient, a measure of pipe roughness affecting flow, is set at 140. Emitter and row spacings are uniformly maintained at 1 foot, representing a typical grid layout in drip irrigation setups. The model calculates soil moisture changes based on net moisture (rainfall minus evapotranspiration) and irrigation, assuming uniform soil properties and moisture distribution. Also, a constant efficiency rate of 45% is assumed for the irrigation system, which does not account for potential variations in system performance. This scenario assumes that the irrigation system has a constant efficiency rate of 45%, regardless of the actual conditions. This means that 45% of the water applied to the system is used by the crops, while the remaining 55% is lost to evaporation, runoff, or other factors.

B. Environmental Conditions

Environmental factors play a crucial role in the simulation. The model generates daily weather conditions, including rainfall and evapotranspiration (ET0) rates. Rainfall is simulated with random values between 0 and 0.5 inches per day, while ET0 rates vary between 0.1 and 0.3 inches. These factors influence the soil moisture balance and irrigation requirements.

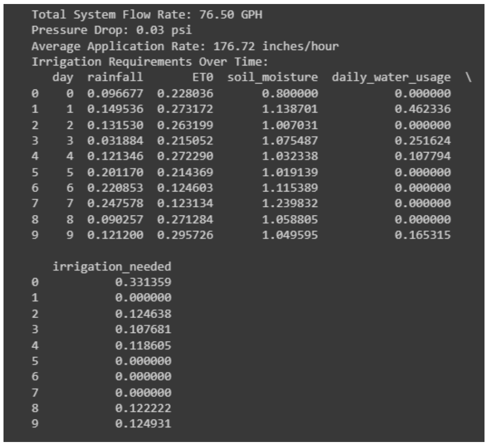
C. Crop Water Requirements

The simulation considers a crop water need of 1.0 inch per week, a standard requirement for many agricultural crops. This need, combined with the simulated environmental conditions, determines the daily irrigation requirements. The area under cultivation is set at 1000 square feet, providing a basis for calculating the total volume of water needed for efficient irrigation.

V. Results

A. Water Use Efficiency Analysis

As shown in Figure3, the water application rate and irrigation time were calculated based on the crop water needs and environmental conditions. The simulation showed that the drip irrigation system could maintain optimal soil moisture levels with less water compared to traditional methods, demonstrating higher water use efficiency.



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Total System Flow Rate: 76.50 GPH
Pressure Drop: 0.03 psi
Average Application Rate: 176.72 inches/hour
Irrigation Requirements Over Time:
   day  rainfall       ET0  soil_moisture  daily_water_usage  \
0    0  0.096677  0.228036       0.800000           0.000000
1    1  0.149536  0.273172       1.138701           0.462336
2    2  0.131530  0.263199       1.007031           0.000000
3    3  0.031884  0.215052       1.075487           0.251624
4    4  0.121346  0.272290       1.032338           0.107794
5    5  0.201170  0.214369       1.019139           0.000000
6    6  0.220853  0.124603       1.115389           0.000000
7    7  0.247578  0.123134       1.239832           0.000000
8    8  0.090257  0.271284       1.058805           0.000000
9    9  0.121200  0.295726       1.049595           0.165315

   irrigation_needed
0           0.331359
1           0.000000
2           0.124638
3           0.107681
4           0.118605
5           0.000000
6           0.000000
7           0.000000
8           0.122222
9           0.124931
```

Fig. 3: Output Results

B. Visualization Techniques

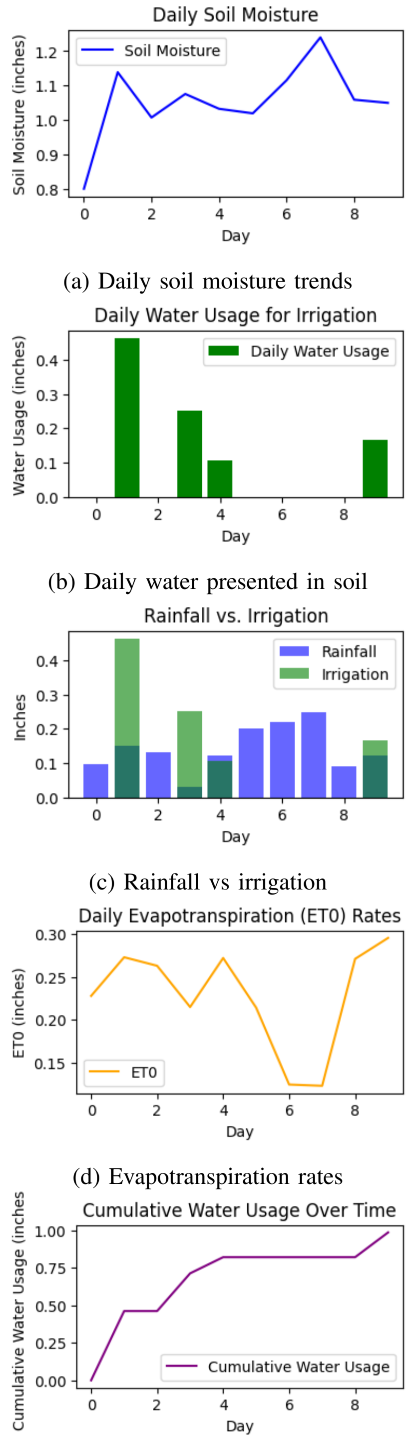
Graphical representations using Matplotlib provide insights into daily soil moisture trends, water usage patterns, rainfall versus irrigation, evapotranspiration rates, and cumulative water usage over the simulation period, as shown in Figure 4.

C. Comparative Analysis

In a study [10] conducted in a soybean (SB) field, soil nitrate (NO3) distribution and crop production were compared under drip and flood irrigation practices. The simulation results align with these findings, showing higher residual NO3 concentrations around the root zone in drip irrigation. This is attributed to the precise and localized application of water, reducing leaching and runoff. Despite the smaller amount of water applied, such simulation suggests potential for higher yields under drip irrigation practices, consistent with the experimental study's findings. Moreover, another study [11] compared to flood irrigation, drip irrigation of Bt. cotton in Haryana led to a 25% reduction in cultivation costs and a 27.2% increase in productivity while saving 33% water. However, challenges like high initial investment, labor intensity, and poor policy support hindered its adoption. The study suggests improved subsidies, farmer training, and investments in quality materials and after-sale service to promote DMI and ensure its potential for sustainable Bt. cotton production in Haryana. Another paper [12] says switching from flood irrigation to drip irrigation for apple trees improved fruit size, weight, color, and marketability. Drip irrigation also uses significantly less water than flood irrigation. This study suggests that drip irrigation is a more sustainable and productive option for apple production.

VI. Discussion

A computational model based on Python is developed to simulate and evaluate the water consumption efficiency of a drip irrigation system. It makes use of libraries such as matplotlib for visualization, pandas for data handling, and Numpy for calculations. Discrete input parameters like emitter flow rates, system dimensions, and initial soil moisture are entered into the model. These inputs are used in the simulation's calculations along with fixed parameters (like pipe dimensions) and environmental factors (like crop water requirements).



(a) Daily soil moisture trends

(b) Daily water presented in soil

(c) Rainfall vs irrigation

(d) Evapotranspiration rates

(e) Cumulative water usage

Fig. 4: Visual Outputs

The simulated drip irrigation system includes multiple emitters (0.5-1.0 GPH flow rates) on a 200-foot 0.75-inch diameter line. Hazen-Williams coefficient of 140 is used, with 1-foot spacing between emitters and rows. Soil moisture changes calculated from net moisture (rainfall minus evapotranspiration) and irrigation, assuming uniform soil properties. The simulation generates daily weather conditions, with simulated rainfall between 0 and 0.5 inches per day and evapotranspiration rates ranging from 0.1 to 0.3 inches. The simulation adopts a standard crop water requirement of 1.0 inch per week.

As per result, we can see that the simulation continues for 10 days. For each day, several parameters such as rainfall, ET0, soil moisture, daily water usage and daily amount of irrigation needed were calculated.

How much water is needed for irrigation is calculated from a function containing rainfall, soil moisture, ET0, etc. That means, it depends upon not one but several important factors. From the result in Fig. 3., we can see that Day 0 represents the first day of initialization where a sensor observes the data and based on that water is used on the following day (theoretically). It should be kept in mind that water needed for irrigation (irrigation_needed) is not the only water the system measures for for daily water usage. Rather, daily water usage is calculated from the summation of water used for irrigation, soil moisture, ET0, and many more factors.

In Day 0, the simulation starts and daily water usage is considered 0 for the first day. The irrigation amount needed is calculated 0.33 inches from the sensor and based upon this, on Day 1, water usage stands at .46 inches. On Day 1, irrigation amount is calculated to be 0, and hence on Day 2, the daily water usage is found to be 0 too. On Day 3, irrigation amount is calculated to be 0.12. As a result, the next day (Day 4), water usage stands at .25. For Day 5,6,and 7, the irrigation amount is predicted to be 0. Hence, for Day 6,7,and 8, the water usage is also calculated to be 0. This is how the simulation continues for all 10 days. Eventually, all the results are visualized in bar charts and line graphs too.

VII. Conclusion and Future Work

The Drip Irrigation System Simulation is an essential tool for transforming crop production, particularly in areas where water scarcity is a problem. Through the skillful modeling of various weather conditions and soil moisture content, this simulation provides a thorough grasp of irrigation requirements, system performance, and water usage over certain periods of time. Users can fine-tune irrigation strategies and optimize system performance with its many features, which include the ability to calculate irrigation demands in line with crop necessities and soil moisture deficits as well as visualize important metrics like soil moisture, evapotranspiration, and rainfall. This simulation, which is aimed at farmers, agricultural engineers, and researchers, provides a means of improving irrigation management techniques, supporting sustainable agricultural methods, and tackling the urgent issues associated with water scarcity in farming.

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