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Prototype Model Design of Automatic Irrigation Controller

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***Abstract*— Irrigation forms one of the primary components of agriculture and food-production. Due to outdated techniques in developing and underdeveloped countries, a huge volume of water is wasted in this process. In this article, we have devised a fuzzy rule-base irrigation controller prototype to put a check on this water wastage by providing an optimal irrigating environment for farming. The prototype Smart Automatic Irrigation Controller (SAIC) has two operational units, viz. Wireless Sensor Unit (WSU) and Wireless Information Processing Unit (WIPU). The purpose of the WSU is to measure weather and soil conditions and calculate the actual water loss due to evapotranspiration. The WIPU processes this calculated value, and perform the necessary control action to regulate the actuators supplying the right amount of water to the farm. An exhaustive rule-base combination model is stacked in the look-up table for decision making. The prototype model is first simulated and then validated in the field for checking the performance efficiency. The simulated results showed capabilities to compensating for water loss by almost 100%. The controller achieved 27% reduction in water usage and a 40% increase in crop yield. The prototype is connected to a cloud-server for data repository and remote access and control. The device is efficient, low cost, and user-friendly so that the end-users can it with ease and comfort. The model is innovative and unique in the sense that it can the irrigation scheduling for all types of crops, across all climatic conditions for all soil types upon feeding the proper soil-crop-growth stage combinations in the inference engine.**

***Index Terms*—Climatic data, Evapotranspiration, Automated, Irrigation, IoT, Water Scheduling.**

I. INTRODUCTION

Among all the natural resources that humankind is fortunate to have, water happens to be the most precious one as it forms the very basis of life and livelihood. Earth has an opulence of this tremendous natural resource, but only a small fraction of it is freshwater and is usable for drinking, agriculture and other life purposes. With population explosion and rapid urbanization of the globe, we are in a dire situation where we need to use this resource tactfully and more efficiently. Freshwater is one of the most important natural resources that is required by the human society along with fresh air to sustain on this planet. But with the advancement of technologies, and increase of population, it is declining at an alarming rate. Again agriculture is one sector which though upgraded with newer techniques and technologies is still a much-neglected sector of research. Countries like India and other developing nations have maintained centuries-old farming methods that have outdated irrigation practices leading to a considerable amount of freshwater wastage because of excessive usage, whereas some areas remain arid. The significant challenges in irrigation are demand for higher productivity, poor performance and lack of availability of freshwater. Agricultural contribution towards Gross Domestic Product is only 15%, and it supports more than 50% of the population [1]. Compared to countries like China, USA and England whose crop productivity is 2 kg per cubic meter, in India, it is only a mere 0.87 kg per cubic meter. About 70 % of the total annual water consumption (550 billion cubic meters) is spent on the agricultural purpose out of which 90% is solely used only to water the farms [2]. With traditional irrigation methods, 2000-3000 litres of water is required for 1 kg of rice [3]. Only by increasing the water utilization rate by 10-15 %, about 40-50 billion kilograms of yield can be improved. Hence it is of utmost importance to pick the right methods and enhance techniques so that we can control the wasting water and use it efficiently in a more organized and controlled manner.

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Therefore to summarize, with the current agricultural practices in countries like India, a huge amount of water is wasted due to improper outdated techniques. At time the farming is over-inundated while at other times, suffers from soil-water stress. This improper conditions also lead to low yield rate from the farming lands.

The primary objective that we have focused in this work is to modernize and automate the irrigation and hence the cultivation procedure, with the aim to reduce water wastage, optimize irrigation requirements, and improve the productivity rate of the cultivated crops. This is how agricultural modernization can be achieved. And to accomplish this modernization, an Irrigation Controller is to be built to fit and cater all the irrigational needs for different types of crops for different climatic conditions across various growth stages [4]. The key features that an Irrigation Controller should be able to provide are high efficiency, low power consumption with minimal investment producing multi-functioning agricultural water-saving platform.

R. G. Allen et al. (1998) [5] developed systems to irrigate farmlands based on the evapotranspirational value and time-based irrigation, which achieved 42% water savings. The article elaborated in detail on Evapotranspiration and parameters on which it is dependent. From here, the elementary idea of Evapotranspiration (ET) and determining factors were learnt, and we understood the evaluation procedure of Evapotranspiration (ET).

K. S. Nemali et al. (2006) [6] developed solenoid valve based irrigation controller applying water to plant beds when the Controller sensed the volumetric water content of the substrate dropping below the set-point value. The model reduced wastage due to leaching and run-off efficiently. However, the model is limited only to the green-house environment and nurseries. The model considered soil-moisture as the only determining factor which may lead to considerable inaccuracies.

S. A. O'Shaughnessy et al. (2010) [7] used remote canopy temperature set-point to automate the irrigation process from cotton irrigation. Here irrigation is triggered automatically when the temperature of the canopy went past the threshold value. This method was proved effective in water usage compared to manual irrigation methods. The method did not consider the total loss due to Evapotranspiration and overlooked the factors like relative humidity, solar radiation and wind speed. The model was also not extended to verify with other crop-type. The water-savings attained due to the application of this model is also not stated.

Zhang Feng et al. (2011) [8] discussed Wireless Sensor Network (WSN) and Internet technology using wireless protocols Wi-Fi [9] and Zigbee [10] for irrigation automation, in order to collect field data and transmit it over to the concerned individual. The critical distance d_0 between the sending and receiving nodes is also calculated as in (1) [8].

$$d_0 = \frac{4\pi\sqrt{\alpha h_r}}{\lambda} h_t \quad (1)$$

Where α is the path loss exponent, h_r is the receiver antenna height, h_t is the transmitting antenna height, λ is the signal wavelength.

In our work, we have utilized the WSN and internet technology and modified its cloud server repository to upload the data for future usage and reference.

Jaoquin Gutierrez et al. (2014) [11] worked on a Wireless Sensor Network and remotely located Controller using duplex cellular-internet communication to automate the irrigation process in a greenhouse environment considering the soil-moisture and temperature as the deciding factors. The internet communication helped monitor irrigation-scheduling via a web page. The model achieved 90% water saving compared to traditional irrigation. However, the other important parameters like relative humidity, wind speed and solar radiation were not considered in this model, and therefore the exact water loss could not be properly determined.

Jason Parmenter et al. (2014) [12] suggested a similar kind of irrigation controller for residential sprinkler based system where Web-based dynamics was proposed that would feature intuitive GUI in cellphones and relinquishing the users from being present at the location. In that work, TI's Beagle Bone Black board provided the constant Internet connectivity both over Ethernet and Wi-Fi adapter. The researchers have designed a Printed Circuit Board model along with the corresponding software. However, one limiting factor of this model is the data storage incapability, which we have incorporated into our work.

For providing data to properly manage the monitoring of environmental, weather and soil-related parameters and storage for future analysis, wireless communication and networking have found high applications, and much advancement has taken place in the field of Wireless Sensor Networks (WSN) [13-15].

Kim et al. (2008) [16] designed distributed wireless sensor network based irrigation system, capturing the different weather readings and wirelessly connected passive capillary wick-type lysimeter to record drained water below the root zone, and connected it to a remote control unit via Bluetooth connectivity [17]. Our design has extended on the system connecting our model to a wireless network and uploading the data to the cloud server to future referencing and exhaustive rule-base to decide on the actuator operation.

Agbetuyi et al. (2016) [18] in the article have designed a soil moisture sensor-based automatic irrigation system which is a stand-alone system and was not connected to any network. Also, the control circuit used was a simple 555 timer-based circuit. However, they later proposed to upgrade the system to a GPRS based system. In their work, they categorized irrigation scheduling into four categories as

a) entirely empirical,

b) soil moisture monitoring based

c) estimation based on weather data and

d) tracking crop condition referring to as crop-water stress.

But the model did not take into account other important parameters like temperature, wind speed, and relative humidity and also did not incorporate data transmission over the internet.

Tiberiu Marinescu et al. (2017) [19] designed a control strategy for vineyards and compared PID control, fuzzy system, decision support system (DSS), and model prediction control (MPC) considering the irrigation system as a multiple-input multiple-output (MIMO) model. The data communication is based on the GSM module. But the model remained as a schematic set-up, and therefore the validity of the scheme is not confirmed.

Erean Avsar et al. (2018) [20] developed a cloud-based automatic irrigation system which is capable of driving sprinklers to compensate for the loss of water recorded on a lysimeter by actuating solenoid valves. The model recorded water level of the lysimeter and temperature, humidity and atmospheric pressure using sensors which are sent to a cloud server. The researchers also developed an Android app for visualizing the sensor outputs and action as taken the Controller. The connection to the cloud server is established with the usage of ZigBee and GPRS communication capabilities. However, the researchers have limited themselves to a controlled agricultural condition for strawberries. The duration of irrigation, as proposed by this team, is cited in (2) [21].

$$t = \frac{E_{pan} * K_{cp} * P * A}{q * n} \quad (2)$$

Where E_{pan} is the cumulative free surface water evaporation at irrigation interval (mm), K_{cp} is the plant-pan coefficient, P is the plant cover (%), a parameter related to the area of plant leaves; A is the field area (m^2); q is the flow rate from the emitters and n is the number of drippers in the field [21]. Our model improved on this concept of cloud server as part of irrigation control and provided an exhaustive look-up reference table for the fuzzy rule-base for decision making under different circumstances. The pros and cons of the different methods carried out previously in the attempt to automate the irrigation process are put in a tabulated manner in Table 1.

Design of irrigation controller using Artificial Neural Network are attempted that showed promising results [22-23] but with limited success. The models were only limited to simulation but not implemented physically. Therefore the practical efficiency is not tested. A case study carried out for 3 years on an area of 210 hectare for six different crops by Ram Vaibhav and his team [24] in Una and Talala taluka of Gujrat, implementing drip-irrigation system tand compared with results against surface irrigation technique. The study showed that an average improvement of 2.13% in crop yield and 40% reduction in water usage were achieved. However, the initial cost of piping arrangement for the drip irrigation were huge. However, in the long run, the micro-irrigation system (MIS) is more productive. Hence we plan to incorporate the MIS in the second field-run of the controller to check for improved results.

A data acquisition system was deployed for monitoring crop conditions employing soil moisture and soil, air, and canopy temperature measurement in cropped fields. Data were downloaded using a handheld computer connected via a serial port for analysis and storage [25]. There are hybrid architectures, wireless modules located inside the greenhouse where high flexibility is required, and wired modules are used in the outside area as actuator controllers [26].

The development of WSNs based on microcontrollers and communication technologies can improve the current methods of monitoring to support the response appropriately in real-time for a wide range of applications [27], considering the requirements of the deployed area, such as terrestrial, underground, underwater, multimedia, and mobile [28]. Here in our work, we have developed a Smart Automatic Irrigation Controller perfecting on the shortfalls of the previous researches. The novelty of this model that it can cater to all crop types, across all growth stages for any soil type through different climatic conditions across the globe, just by feeding the proper rule-base for all these different combinations. These features make it a unique irrigation controller set-up.

However, there are two challenges in this model. The first challenge is to design an accurate and exhaustive rule-base which depends largely on securing sufficient volume of data-set for any particular crop-soil-growth combination, as insufficiency in data may lead to less effective and erroneous outcome. The second challenge is initial installation of the sensor-network and controller module in the field that needs proper expertized handling and involves significant initial cost involvement. Also, the current model is not very efficient for small-scale farming. Our team is working to remedy these short comings to develop even a better and more universal model to eliminate the shortfalls.

II. Smart Automatic Irrigation Controller

Irrigation mechanism is a supplementary method of providing water to irrigation fields for maintaining crop health and aesthetics. Atmospheric parameters' measurement, soil and crop type and requirements offer significant information on the

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yield from previous actions and assist in calculating the next irrigation practice, which can be obtained by introducing a feedback loop in the Controller [29]. The three key players in agriculture are weather, soil and crop. Changing the weather is beyond help, but based on that and crop information, supplements can be added to the land to acquire the desired yield.

The basic idea behind designing an irrigation controller is to attain a better and more efficient water management set-up that will maintain water quality and will assist the implementers with a firm and sound water management schemes by which we will be able to maintain and manage good farmland. There exists a lot of automatic irrigation methods viz. time-based system, volume-based system, open-loop system, closed-loop system, real-time feedback system but the one that is in the most desirable position is the computer/Controller based irrigation control system. Again based on the complexity of the technology, it is also categorized as a low-tech principle and high-tech principle [30-33]. From the above discussion, it boils down to the point that the controlled irrigation system is either of mechanical type or is electronically controlled. The tradeoff that exists with the idea of irrigation controllers is that it is an expensive procedure at the initial stages and it requires a constant power supply system which is a reasonable sacrifice considering the advantages the controlled system can provide.

Between March and June in India, as the days get longer and warmer, Evapotranspiration (ET) value increases, and also the plants' need for water, gradually increases. The length of the day, temperature, humidity, and rainfall, solar radiation and wind speed are all factors of watering schedules. Traditional irrigation controllers are turned off during the rainy seasons, i.e. between July and September. When rain usually ends in October, present-day irrigation controllers are turned on and then left running on a preset schedule until well into the monsoon when it begins raining again. These pre-set schedules water too much on some days and not enough on others, either wasting water or causing plant stress. More efficient irrigation scheduling would read the system run times to match the changing plant water needs daily, and it would water them lesser as days get colder and shorter in the fall.

Evapotranspiration (ET) irrigation controllers re-adjust themselves automatically as often as needed without manual intervention by using three sources of information:

1. Real-time weather and climatic sensor data to calculate actual evapotranspiration losses.
2. Geographic locations, soil type, irrigation type.
3. Plantation type, growth stage.

The other parameter of concern is the Soil Moisture Deficit (SMD) which indicates the water requirement of the soil to maintain the field capacity. SMD is a function of incoming water, outgoing potential ET and water capacity available for plant use.

The ET is calculated from the basic equation as in (3) [34] below.

$$ET = I + P - RO - DP + CR \pm DSF \pm DSW \quad (3)$$

I=Irrigation; P=Rainfall; RO=Run Off; DP=Deep Percolation; CR=Capillary Rise; DSF=Subsurface flow in the root zone (negligible); DSW=Subsurface flow out of the root zone (negligible)

The Penman-Monteith (PM) [35] equation (4) which is categorized as a combined method for evapotranspiration determination is one of the most widely accepted methods for ET calculation.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (4)$$

ET_0 = Reference evapotranspiration [mm day-1], R_n= Net radiation at the crop surface [MJ m-2 day-1],

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G = Soil heat flux density [MJ m-2 day-1], T = Mean daily air temperature at 2 m height [°C],

U_2 = Wind speed at 2 m height [m/s], e_s= Saturation vapour pressure [kPa],

e_a= Actual vapour pressure [kPa], $e_s - e_a = e^0(T)$ = Saturation vapour pressure deficit [kPa],

D = Slope vapour pressure curve [kPa °C-1], g = Psychometric constant [kPa/ °C].

P = Atmospheric pressure [kPa], z = Elevation above sea level [m],

e^0(T) = Saturation vapour pressure at the air temperature T [kPa],

λ = Latent heat of vaporisation, 2.45 [MJ kg-1],

C_p = Specific heat at constant pressure, 1.013 10-3 [MJkg-1 °C-1],

ε = Ratio molecular weight of water vapour/dry air =0.622

However, this is not always accurate and sometimes based on the geographical location; one has to resort to other empirical methods for ET determination. It has been found that Kharrufa method (5) [36] is the most efficient method when temperature-based method [37] is considered, and Hargreaves and Samani method (6) [38] is the most effective one considering the radiation-based methods [39].

$$ET = 0.34 * p * T_a^{1.3} \quad (5)$$

$$ET_o = 0.0135 R_s (T_{mean} + 17.8) \quad (6)$$

Where p = % of total daytime hours for the period of measurement, T_a = mean monthly temperature; R_s = Solar radiation; T_{mean} = daily mean temperature.

Now it has to be evaluated and determined on which manner is more efficient and accurate for what kind of climatic and geographic conditions. Based on this information, the Controller will first decide on which way to use for ET determination and then decide on how much water should be supplied to the field to maintain the optimal conditions. As an additional feature, the Controller is also equipped with sensors to monitor and evaluate the quality of water that has to be supplied and based on the need and requirement of the soil type and crop type, and it will regulate the quality of the water to maintain hospitable conditions. It is not a direct section of the Controller but an additional set-up providing more efficiency to the irrigation controller.

The block diagram of the Smart Automatic Irrigation Controller is shown in Fig. 1 below, which shows acquiring of weather and field data through specialized sensors and how the data is evaluated for ET determination and decision on water disbursing. The Poyen's flowchart of the operation of the designed irrigation controller is illustrated in Fig 2 below. It is evident from the flowchart that in case, sufficient rainfall is recorded, then the irrigation procedure is not initiated. The flowchart works as a continuous feedback loop so that the redundant supply of water can be prevented.

The Poyen's SAIC algorithm of operation of the Automatic Irrigation Controller in reference to the flowchart as shown in Fig 2 is elaborated here.

Step 1: The system acquires data from the sensor network as placed in the field and the smart weather-station.

Step 2: The WSU and WIPU establish the connection with the cloud server for data transmission and receiving via I2C protocol.

Step 3: On receiving sensor data, the WIPU calculates the evapotranspiration loss.

Step 4: The rule-base in the look-up table is referred to for determination of the water compensation based on soil-crop-growth level water requirement combinations as inferred by the Fuzzy Inference Engine.

Step 5: In case of no compensation requirement, no action is taken, but in case compensation is required, the system looks for water compensation due to rainfall.

Step 6: If sufficient rainfall compensates for the lost water, no action is required. Otherwise, the WIPU controller directs the actuator to make up for the water loss.

Step 7: pH sensor continuously measure the pH value of both supplied water and soil.

Step 8: The process is run continuously with a feedback loop, and the optimum water level is maintained in the farm land.

By abiding with this algorithm, the farmland receives just the most optimum levels of water, and hence an increase in productivity is projected. As mentioned earlier of the supplementary process, once the water is fed to the farmland, the pH sensors measure the water pH levels and based on the soil pH requirement, it would mix acid or lime to the reservoir water to maintain the required soil pH levels [40]. The standing water level requirements for the different crop-soil-growth combinations are tabulated in Table 2.

III. Study Area

As the essential requirement of this article is to collect, record, analyze, display and calculate values and finally to control actuators for controlled irrigation, it is necessary to collect actual field data from a geographical area. The study area chosen in this investigational set-up is Burdwan which is located primarily on a dominant agriculture belt. Because there already exists a weather substation, it is easier to validate the data received from the sensor network against the station data. The field study was carried on a 1 acre of farming land which is low in nitrogen, calcium, phosphate and other plant nutrients, and the soil type is alluvial sandy clays to loamy and slightly acidic.

Study Area: Bardhaman, District: Burdwan, State: West Bengal, Country: India.

Latitude/longitude: 23°15′20″N 87°51′24″E

Decimal coordinates: 23.2557 87.8569

Category: Suburban Township; Region: West Bengal, India; Time Zone: Asia/Kolkata.

Population: 301725; Geonames - ID: 1277029; Total Area: 59 km²

Climate is tropical, and the average annual temperature is 26.3 °C, and the average altitude is 32 m. The variation of temperature throughout the year is 11.5 °C and the difference of precipitation between the driest and wettest months is 307 mm. April is the warmest month with an average temperature of 30.9 °C and January is the coldest with an average of 19.4 °C. The Köppen-Geiger climate classification is Aw (Tropical, Savanna wet). The average rainfall is 1313 mm with the monsoon months being July, August, September and first part of October.

This area is a typical agricultural township.

The selection of this study area is justified by the fact that it is predominantly an irrigation-based locality with the principle crop harvested being rice that is the staple crop of West Bengal.

The total area of farming land that has been considered on a pilot scale is 1 acre (university farm)(farm dimension is 61X66 m2) with perfect and optimum cultivating conditions, i.e. uniformly grained, slightly alluvial and lightly acidic in nature having little nitrogen, calcium and phosphate content that increase the requirement of fertilizer usage [41]. Currently, we have compared the yields of two successive seasons and will extend the study over multiple seasons on different plots to establish more concrete statistical significance.

IV. Components and Equipment

Sensors for measuring and recording air temperature (DHT22) and soil temperature (DS18B20), relative humidity (DHT22), atmospheric pressure (BMP180), soil moisture sensor (YL-69), superfluous water level sensor (HC-SR04) in the farmland and reservoir, soil pH sensor (SEN0249) wind speed (A3144 Hall), light intensity (BH1750) and solar radiation employing voltage and current (ACS712) sensors built the sensor matrix. One 1 HP pump with a pipe diameter of 1.5 inches with an output capacity of 42 GPM to supply the water, Control valve for the reservoir and acid and lime tanks, flow meter regulates the water, acid and lime flow. The water-pump was the only artificial water source, and no canal irrigation or other types of irrigation methods were applied. The Water reservoir, acid and alkali tanks are the repository units. Wi-Fi module is used to communicate the cloud server and data exchange. A power supply of 240 V 1-Phase unit supplies power up the entire set-up. Sprinkler arrangement assures uniform distribution of water. Table 3 lists the equipment and instruments used in building the model with their number, type, model and locations. The device characteristics of the sensors are tabulated in Table 4.

V. Design of the SAIC

In this section, the detailed physical description of the Smart Automatic Irrigation Controller (SAIC) is provided. The SAIC has two separate control units, the first part is the Wireless Sensor Unit (WSU), and the second part is the Wireless Information Processing Unit (WIPU). The internal functional block schematic and the front panel schematic of WIPU are illustrated in Fig 3 and Fig 4, respectively. These two sections work in unison to deliver the desired irrigation control, i.e. regulating the supply of water to the target location. The function of the WSU is to sense, measure, and record climatic data and based on those, calculate the ET value, which is subsequently uploaded in the cloud server. The WIPU downloads these data from the cloud then processes the data and makes the necessary decisions on when and how much volume of water to be supplied. The controller section of the WIPU is programmed with the fuzzy logic rule-base based on which the actuator is driven. At the actuator end, a feedback loop is created so that the valve operations can be controlled. The WSU unit is located in the study area, i.e. the field where the farming is ongoing whereas the WIPU is situated elsewhere, from where it can be duly monitored thus freeing the process from any workforce involvement. The second Controller forms a closed-loop feedback system to monitor the pH levels of supplied water constantly and operates on the liming or acidification action to regulate the water quality and maintain the desired pH levels. Furthermore, the WSU and WIPU can select between any of the four principle ET evaluating processes viz. combined method, temperature-based method, radiation-based method and mass-transfer based method as the geographical location and climatic conditions demand. Thus the irrigation controller provides a lot of flexibility to the user to accommodate the specific kind of requirement.

The array of sensors is connected with the microcontroller unit of the WSU to measure and record climatic data daily in continuous mode to avail round the clock weather information. The climatic parameters that are being recorded are air temperature, relative humidity, soil moisture content, soil temperature, solar radiation, wind speed, rainfall, and atmospheric pressure along with light intensity. The data measured is sent to the processing unit to determine the ET value based on any of the ET methods selected as finding best for that particular geographical location. The values recorded and calculated at WSU end is sent to the ThingSpeak cloud server, which is a free data repository. The WIPU downloads these data and compare the ET value with desired ET values and based on the results obtained, the WIPU decides on whether or not to initiate the pump to supply water to the field. Figure 5 shows the system architecture with the IoT framework.

The first step of this project is acquiring weather and field data via sensors and evaluating on ET which feeding to the controller unit plans for the watering schedule. Once this is successfully accomplished, the next step is to uplink the entire set-up on the cloud via the Internet of Things (IoT) which makes the system smart in true sense. Fig 6 demonstrates how the set-up is connected to a cloud server via Wi-Fi (IEEE 802.11) module by which it is capable of storing the data received by the sensors in a remote server from where these data can be accessed by anyone on request. This enables other researchers to contribute their findings and exchange information for further investigation and improvements. The Controller has one transmitting and one receiving module through which it uploads data to the server and receives relevant climatic and soil, crop and growth stage requirement data from the servers. The set-up is accessorized with a display unit that provides a quick readout of the proceedings that are taking place. An antenna of 2.4 GHz frequency is used at the WIPU with a range of 1 km for reliable and robust connectivity.

VI. Set-up, Results and Discussion

The experimental test run was conducted on rice cultivation which is a primarily a Kharif crop. Rice is the staple crop of the study region and the period of study was from the fallow period to the harvesting period for a medium duration rice variant which has a growth duration of 120 to 140 days. The cultivation season is of Aman type, i.e. the seeds are sown in winter and harvested in the summer. The Aman season (November – March) is chosen as during this period there is mild to no rainfall, and the cultivation primarily depends on irrigation water.

The entire study region is divided into four zones, each having a separate WSU. One stand-alone digital weather station is built as part of this set-up is shown in Fig 7. The data recorded by the four individual WSUs are sent to the cloud server where the mean value is calculated and stored. The sensor function, type, number and location are tabulated in Table 3. The sensors form a network and a digital weather station to monitor the conditions and determine the water loss by ET every day. The air temperature sensor (DHT22), humidity sensor (DHT22), atmospheric pressure sensor (BMP180), hall based anemometer (A3144), light intensity sensor (BH1750), solar radiation using one solar panel (12V, 20W) and current sensor (ACS712) and voltage sensor are mounted on the smart weather station and WSU. Four sensors, each for soil moisture sensors (YL-69), soil temperature sensors (DS18B20), and soil pH sensor (SEN0249) are placed at the four boundary points buried in the field at a depth of 20 cm. Four level sensors (HC-SR04) are placed at the four corners of the field at a height of 25 cm to measure the standing water levels. The internal circuit diagram with the sensor mounted on it is shown in Fig 8.

The software platform used for the coding purpose is open-source Arduino IDE1.8.8 in which the entire program is written, debugged and executed.

Real-Time Data processing is the core of the system on which the efficiency depends. As part of the experimental set-up to build the automatic irrigation controller, Arduino Nano for WSU and ESP32 SOC (system on chip) for WIPU have been used as the controller units which would first acquire climatic and weather data from a set of parameter-specific sensors. The internal circuit connection of WIPU is shown in Fig 9. Once the data is received by the controller unit (analogue or digital form), it will be processed to calculate the daily Evapotranspiration rate. The processor used in the

Arduino Nano is ATmega 328p with a processing speed of 16 MHz, and power supply requirement of 5 V. Generic ESP32 module is used with the Arduino Nano to transmit data to the cloud. Tensilica Xtensa LX6 microprocessor is used in the ESP32 SOC which operates at 240 MHz and runs of 3.3 V power supply. The ESP32 has in-built Wi-Fi and Bluetooth connectivity. Along with the ESP32, SIM800C GSM/GPRS module is used to establish the wireless connectivity required to upload and download data from the cloud server. SIM800C has an operating frequency of 1900MHz with significantly low power requirement, and it can upload/download data at a maximum speed of 85.6 kbps.

The WIPU consists of the GSM/GPRS module (SIM 800C), a NodeMCU ESP32, and a relay unit to trigger the 1 HP pump (220 V, 50 HZ AC). The objective of the WIPU is to receive data from the ThingSpeak server, compare the measured ET value with the required ET value referring to a look-up table database for the irrigation requirement of different crops, and soil types. The data uploading and storage in the cloud server is illustrated in Fig 10. For downloading these look-up data from server to NodeMCU, GSM/GPRS module provides internet connection. Rx, Tx and GND of SIM800C are connected to Tx, Rx and GND pins of NodeMCU. A regular subscriber identification module (SIM) card is attached to SIM800C for providing network connectivity, and according to the service provider of the SIM800C, the Access Point Name (APN) settings is written in the code. After the connection is set up with the network, the exact URL of the server from which data is to be fetched, along with the GET request is provided in the code. Thus the data in the server is downloaded, and the processing is done in Nodemcu.

ESP32 NodeMCU has an extra feature of different sleep modes. These modes are used for power saving purposes of the module. When ESP32 enters sleep mode, power is cut to any not needed digital peripherals, while RAM receives just enough power to enable it to retain its data. Different sleep modes of ESP32 are –

1. Active,
2. Modem Sleep,
3. Light Sleep,
4. Deep Sleep,
5. Hibernation Mode

In Deep Sleep Mode, power consumption by the Multipoint Control Unit (MCU) is meagre (approx. 10 μA). In this mode, ULP and RTC of ESP32 are active, but other core MCU, peripherals, WIFI, Bluetooth remain inactive. For particular values of data or a constant periodic interval, these inactive sections become active. Core MCU, peripherals, Wi-Fi remain inactive for one hour and momentarily becomes active for few seconds to receive data, compare and show data and depending on that pump is actuated. Thus the WIPU can operate in meagre power ratings.

The WIPU is housed in an 8X6 inches PVC box along with the power supply lines, the necessary push button and knob switches for selecting the different parameters as per the requirement. The control box also has a 20X4 LCD to show the different parameters that are chosen for operation and the climatic parameters along with the date, time and timer. The antenna module provides a communication module over a distance of 1 km and operates at 2.4 GHz frequency. The input power supply to the junction box is 230 V AC, 50 Hz which is internally converted to 5 V and 12 V.

The Selection Considerations that are to be made by the WSU and WIPU are

1. Soil Type (Sandy, Loam, Silty, Clay) by the WSU,
2. Crop Type (floral plants, trees, shrubs, farmland) by the WSU,

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3. Irrigation Type (Spray head, rotor, drip emitter, impact bubbler) by the WIPU,
4. Microclimate (Sunny All day, Sunny most part of the day, shady all day, shady most part of the day) by the WIPU,
5. Slope (0-5%, 5-10%, 10-15%, 15-20%, >20%) by the WIPU.

All these data are pre-fed to the Controller so that the Controller can calculate the required ET values and determine how much supply of water will achieve that value. The checklist for the Controller is provided as below:

1. Check for soil,
2. Check for crop type (rice, wheat, barley),
3. Check for the stage of growth (field preparation, planting, panicle initiation, flowering, maturity),
4. Check for Controller,
5. Check for Obstructions,
6. Check for Wear & Tear of Pump,
7. Check for Valve,
8. Check for Serge,
9. Check Water Pressure

The experimental procedure was carried out for 140 days starting from the first ploughing to harvesting between 10^{th} November 2018 and 31^{st} March 2019. Each day's climatic and field data viz. air temperature, soil temperature, wind speed, relative humidity, atmospheric pressure, solar radiation, soil moisture levels, the water level in the field (if any) were collected and recorded. Also, the soil pH value was recorded. It is observed that the pH values varied between 6.6 and 7.5 during the entire period, which is optimum for rice growth. Hence no neutralization was required. During this period, sporadic rainfall was received, and hence the total water that was supplied was primarily by irrigation. For the first 30 days of growth, the water level maintained is 8 cm, and then for the next 80 days, the water level is maintained at 15 cm. Studies showed that about 40% of the required water is lost in Evapotranspiration and 60% is lost in percolation [3]. Thus after determining the daily value of ET, 2.5 times of the same is recouped to the field to maintain the required balance of water table in the field. Table 5 shows the monthly average of the data collected from sensors, calculated ET obtained from WSU and actual ET measured from a weighing Lysimeter. The results show that ET value calculated is almost equal to the lysimeter ET value, and hence it can be concluded that the calculated ET is correct. These data are obtained from the pilot smart weather station that is built during the process of this experiment, and the results are validated from other established and official weather stations.

The results obtained while comparing the two successive yields are tabulated in Table 6. The amount of water required to cultivate 1 acre of land without the employment of the SAIC was previously 7.2 million litres with a yield of 2.2 tons with no irrigation automation method employed. On employing the SAIC on the same area of farmland, the amount of water supplied is 5.56 million litres over a period of 140 days and the yield recorded is 3.1 tons. The cultivation period in both cases is 140 days, with approximately the same climatic conditions. Thus it is found that both savings of large volume of water and increase in yield are obtained due to the application of the SAIC. No additional acid or alkaline solution was required for this experiment. Therefore, it is observed that 27% of irrigation water is saved and 40% of the increase in yield is obtained due to the application of the SAIC. However, there are also other factors like weed and pest control and the usage of fertilizers that contributed to the increase of yield. The cost of procurement in USD (United States Dollar) of the sensors and equipment and assembling the whole set-up including the 1 HP AC submersible pumps is USD 160 (INR 12000). Circuit minimization, component optimization and large scale production will bright out the unit manufacturing cost significantly. The electrical unit consumed was 1680 units amounting to USD 115 (INR 8400) without the controller, and the unit consumed 1300 amounting to USD 90 (INR 6500) without the controller in place. Thus a cost reduction of USD 25 (INR 1900) i.e. 23% was achieved. The current cost of automatic piping and water scheduling of 1 acre land comes around USD 340 (INR 25000) without any sophisticated control action, which includes the manufacturing cost, profit and other ancillary expenses. So we can safely claim that our prototype model is more cost-effective than the existing watering controllers available.

VII. Conclusion

The prototype model of IoT based Automatic Irrigation Controller is named as Smart Automatic Irrigation Controller (SAIC). The simulation and field-study results showed that water usage is reduced by 27% and production yield is improved by 40%. So it is satisfactorily inferred that the objectives of the model i.e. reduction of water usage and wastage and improvement in product yield are successfully achieved. The ease of operation and low cost, and high efficiency are the unique selling point (USP) of this device. The data uploaded in the cloud-server can be accessed by other researchers providing the platform for live feedback and discussion on the betterment of the process. Thus it can have a significant impact in the irrigation scheduling process and agriculture in the long run. We are now working on minimizing the circuit board and configuring the set-up in a more robust and compact manner for easy mobility and less-careful and handling by the non-expert end-users. . Large scale production of this device will further bring down the cost, and it has the potential to cater to all types of cultivators. We also aim to incorporate the automation of fertization process with this system. We also look forward to implement the model using other control logic like ANN, MPC and others.

References

[1] G. Kaur, "Budget 2020: Agriculture Key in Revival of Economy", grainmart.in, 2020.

[2] F. Poyen, "Automated Watering System for Agricultural Fields", *International Journal of Advances in Electronics Engineering*, vol. 2, no. 3, pp. 104-107, 2012.

[3] “Irrigation water management in paddy | agropedia", *Agropedia.iitk.ac.in*, 2018. [Online]. Available: http://agropedia.iitk.ac.in/content/irrigation-water-management-paddy.

[4] *Irrigation.org*, 2019. [Online]. Available: https://www.irrigation.org/IA/FileUploads/IA/Advocacy/Principles_of_Efficient_Agriculture_Irrigation_7-17.pdf.

[5] R. Allen, L. Pereira, D. Raes and M. Smith, "Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56", *FAO - Food and Agriculture Organization of the United Nations Rome, 1998*, pp. 2-5, 1998.

[6] K. Nemali and M. van Iersel, "An automated system for controlling drought stress and irrigation in potted plants", *Scientia Horticulturae*, vol. 110, no. 3, pp. 292-297, 2006. DOI: 10.1016/j.scienta.2006.07.009.

[7] S. O'Shaughnessy and S. Evett, "Canopy temperature based system effectively schedules and controls center pivot irrigation of cotton", *Agricultural Water Management*, vol. 97, no. 9, pp. 1310-1316, 2010. DOI: 10.1016/j.agwat.2010.03.012.

[8] Zhang Feng, "Research on water-saving irrigation automatic control system based on

internet of things", *2011 International Conference on Electric Information and Control Engineering*, 2011. DOI: 10.1109/iceice.2011.5778297.

[9] "IEEE Standard for Information Technology - Telecommunications and information exchange between systems - Local and Metropolitan networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Higher Speed Physical Layer (PHY) Extension in the 2.4 GHz band", 2000. DOI: 10.1109/ieeestd.2000.90914.

[10] "IEEE Standard for Information technology-- Local and metropolitan area networks-- Specific requirements-- Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (WPANs)", 2006. DOI: 10.1109/ieeestd.2006.232110.

[11] J. Gutierrez, J. Villa-Medina, A. Nieto-Garibay and M. Porta-Gandara, "Automated Irrigation System Using a Wireless Sensor Network and GPRS Module", *IEEE Transactions on Instrumentation and Measurement*, vol. 63, no. 1, pp. 166-176, 2014. DOI: 10.1109/tim.2013.2276487.

[12] J. Parmenter, A. Jensen and S. Chiu, "Smart irrigation controller", *IEEE International Conference on Electro/Information Technology*, 2014. DOI: 10.1109/eit.2014.6871796.

[13] N. Wang, N. Zhang and M. Wang, "Wireless sensors in agriculture and food industry—Recent development and future perspective", *Computers and Electronics in Agriculture*, vol. 50, no. 1, pp. 1-14, 2006. DOI: 10.1016/j.compag.2005.09.003.

[14] D. Chaudhary, S. Nayse and L. Waghmare, "Application of Wireless Sensor Networks for Greenhouse Parameter Control in Precision Agriculture", *International Journal of Wireless & Mobile Networks*, vol. 3, no. 1, pp. 140-149, 2011. DOI: 10.5121/ijwmn.2011.3113.

[15] P. Marino, F. Fontan, M. Dominguez and S. Otero, "An Experimental Ad-Hoc WSN for the Instrumentation of Biological Models", *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 11, pp. 2936-2948, 2010. DOI: 10.1109/tim.2010.2045970.

[16] Yunseop Kim, R. Evans and W. Iversen, "Remote Sensing and Control of an Irrigation System Using a Distributed Wireless Sensor Network", *IEEE Transactions on Instrumentation and Measurement*, vol. 57, no. 7, pp. 1379-1387, 2008. DOI: 10.1109/tim.2008.917198.

[17] Y. Kim, J. Jabro and R. Evans, "Wireless lysimeters for real-time online soil water monitoring", *Irrigation Science*, vol. 29, no. 5, pp. 423-430, 2010. DOI: 10.1007/s00271-010-0249-x.

[18] A. Felix, H. Orovwode, A. Awelewa, S. Wara and O. Tobiloba, "DESIGN AND IMPLEMENTATION OF AN AUTOMATIC IRRIGATION SYSTEM BASED ON MONITORING SOIL MOISTURE", *Journal of Electrical Engineering*, vol. 16, pp. 2016-215, 2016.

[19] T. Marinescu et al., "Advanced control strategies for irrigation systems", *2017 9th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS)*, 2017. DOI: 10.1109/idaacs.2017.8095206.

[20] E. Avsar, K. Bulus, M. Saridas and B. Kapur, "Development of a cloud-based automatic irrigation system: A case study on strawberry cultivation", *2018 7th International Conference on Modern Circuits and Systems Technologies (MOCAST)*, 2018. DOI: 10.1109/mocast.2018.8376641.

[21] İ. TAŞ and H. KIRNAK, "Empirical Models Used in the Estimation of Crop Evapotranspiration in Semi Arid Region of Turkey", *ADÜ Ziraat Fakültesi Dergisi*, vol. 8, no. 1, pp. 57-66, 2011.

[22] S. Aggarwal and A. Kumar, "A Smart Irrigation System to Automate Irrigation Process Using IOT and Artificial Neural Network", in *International Conference on Signal Processing and Communication*, Coimbatore, 2019, pp. 310-314.

[23] S. Umair and R. Usman, "Automation of Irrigation System Using ANN based Controller", *International Journal of Electrical & Computer Sciences*, vol. 10, no. 2, pp. 41-47, 2010.

[24] R. Vaibhav and A. Makwana, "Case study: Impact analysis of Micro Irrigation System in Kodinar Region of Gujarat", *Trends in Biosciences*, vol. 10, no. 48, pp. 9609-9612, 2017.

[25] D. Fisher and H. Kebede, "A low-cost microcontroller-based system to monitor crop temperature and water status", *Computers and Electronics in Agriculture*, vol. 74, no. 1, pp. 168-173, 2010. DOI: 10.1016/j.compag.2010.07.006.

[26] O. Mirabella and M. Brischetto, "A Hybrid Wired/Wireless Networking Infrastructure for Greenhouse Management", *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 2, pp. 398-407, 2011. DOI: 10.1109/tim.2010.2084250.

[27] I. Akyildiz, Weilian Su, Y. Sankarasubramaniam and E. Cayirci, "A survey on sensor networks", *IEEE Communications Magazine*, vol. 40, no. 8, pp. 102-114, 2002. DOI: 10.1109/mcom.2002.1024422.

[28] J. Yick, B. Mukherjee and D. Ghosal, "Wireless sensor network survey", *Computer Networks*, vol. 52, no. 12, pp. 2292-2330, 2008. DOI: 10.1016/j.comnet.2008.04.002.

[29] R. Romero, J. Muriel, I. García and D. Muñoz de la Peña, "Research on automatic irrigation control: State of the art and recent results", *Agricultural Water Management*, vol. 114, pp. 59-66, 2012. DOI: 10.1016/j.agwat.2012.06.026.

[30] B. Stauffer and D. Spuhler, *Automatic Irrigation*. 2018.

[31] A. Benzekri, K. Meghriche and L. Refoufi, "PC-Based Automation of a Multi-Mode Control for an Irrigation System", in *International Symposium on Industrial Embedded Systems*, Lisbon, Portugal, 2007, pp. 310-315.

[32] D. RAJAKUMAR, K. RAMAH, S. RATHIKA and G. THIYAGARAJAN, "Automation in Micro-Irrigation", Technology Innovation Management and Entrepreneurship Information Service, New Delhi, 2008.

[33] B. BOMAN, S. SMITH and B. TULLOS, "Control and Automation in Citrus Microirrigation Systems", *Agricultural and Biological Engineering Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida*, pp. 1-15, 2006.

[34] R. Hilten, T. Lawrence and E. Tollner, "Modeling stormwater runoff from green roofs with HYDRUS-1D", Journal of

Hydrology, vol. 358, no. 3-4, pp. 288-293, 2008. DOI: 10.1016/j.jhydrol.2008.06.010.

[35] R. Allen, L. Pereira, D. Raes and M. Smith, "Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56", *FAO - Food and Agriculture Organization of the United Nations Rome, 1998*, pp. 17, 1998.

[36] N. Kharrufa, “Simplified Equation for Evapotranspiration in Arid Regions”, Beitrage zur Hydrologie, vol. 5, no. 1, pp. 39-47, 1985.

[37] F. Poyen, P. Kundu and A. Ghosh, "Temperature based ET Method Selection for Burdwan District in WB, INDIA", *International Journal of Applied Engineering Research*, vol. 13, no. 16, pp. 12753 - 12763, 2018.

[38] G. Hargreaves and Z. Samani, “Estimation of Potential Evapotranspiration”, Journal of Irrigation and Drainage Division, vol. 108, no. 1, pp. 223-230. 1982.

[39] F. Poyen, A. Ghosh and P. Kundu, “Selection of the most suitable Radiation-based ET method for Burdwan”, International Journal of Scientific & Technology Research, vol. 9, no. 3, pp. 5569-5584. 2020.

[40] F. Poyen, P. Kundu and A. Ghosh, "pH Control of Untreated Water for Irrigation", *Journal of The Institution of Engineers (India): Series A*, vol. 99, no. 3, pp. 539-546, 2018. DOI: 10.1007/s40030-018-0297-4.

[41] "Geography: Burdwan District", *Bardhaman.nic.in*, 2018. [Online]. Available: http://www.bardhaman.nic.in/geography.html.

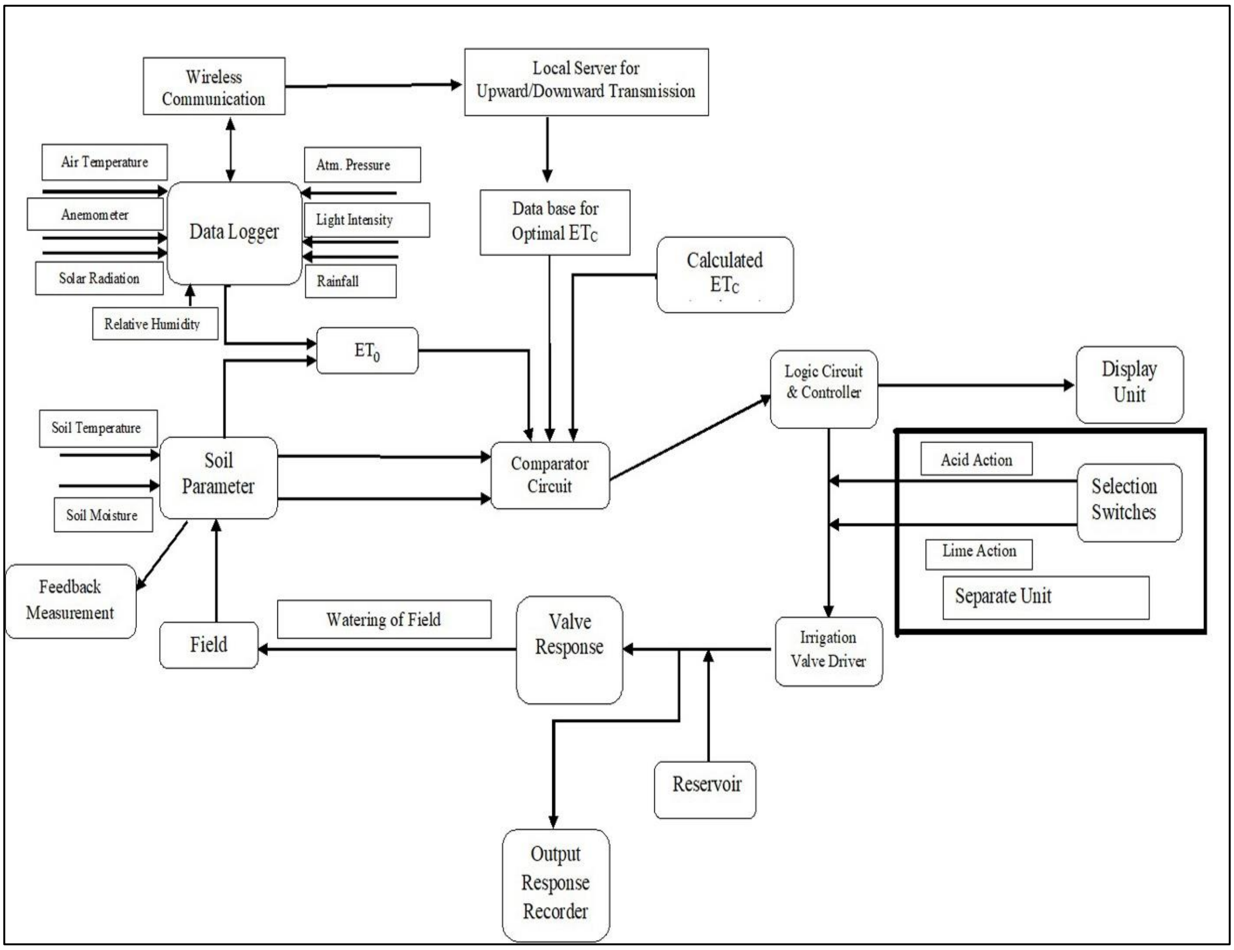

Fig. 1. Block Diagram of the Smart Automatic Irrigation Controller

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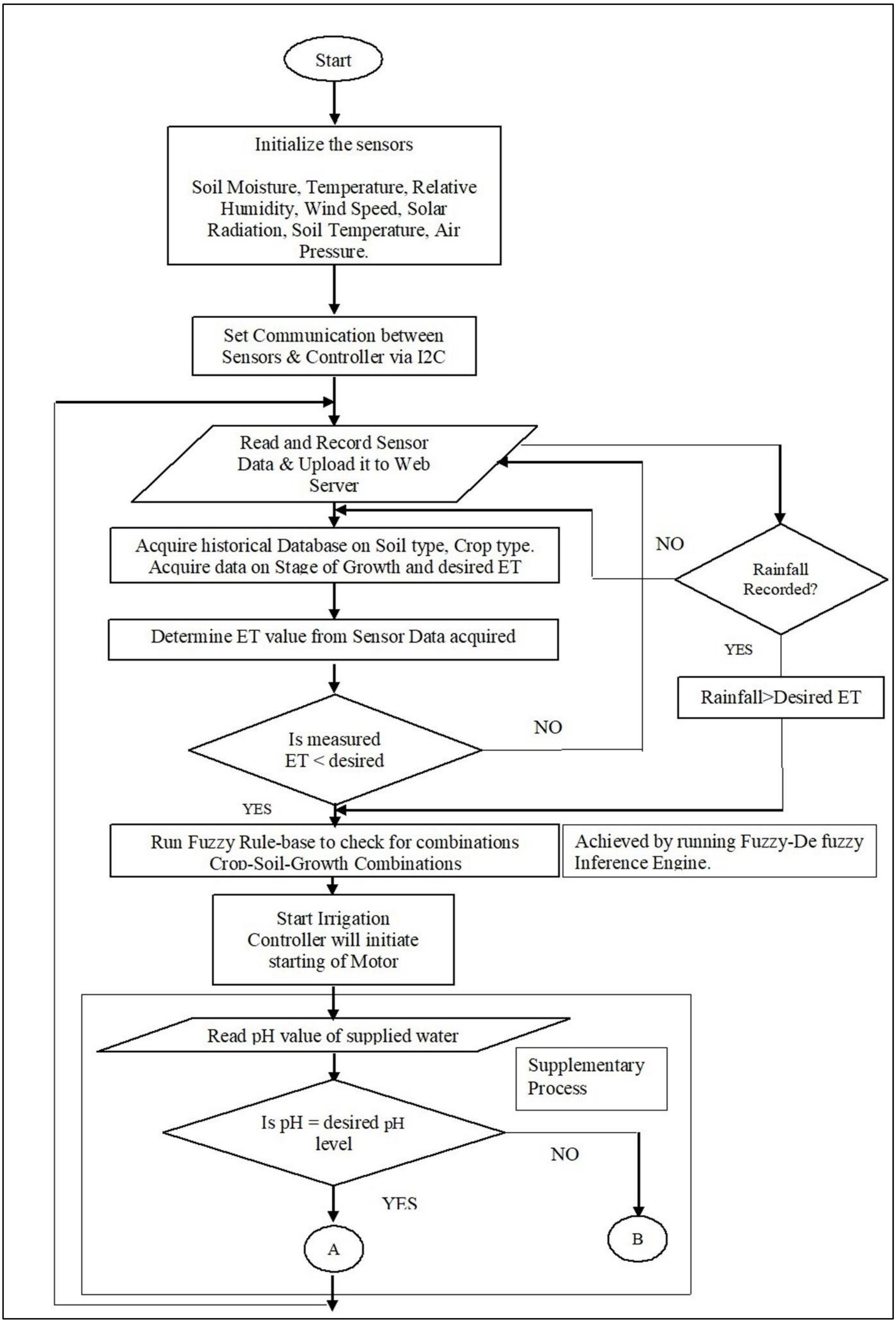

Fig. 2. Flow Chart of the Smart Automatic Irrigation Controller

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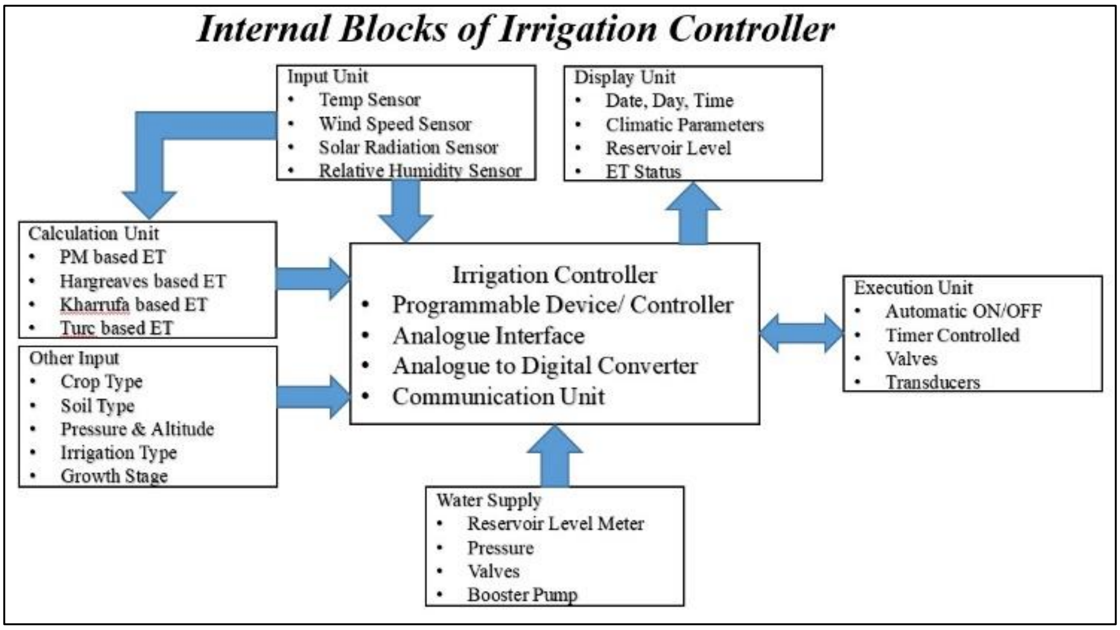

Fig 3: Internal Functional Blocks of SAIC

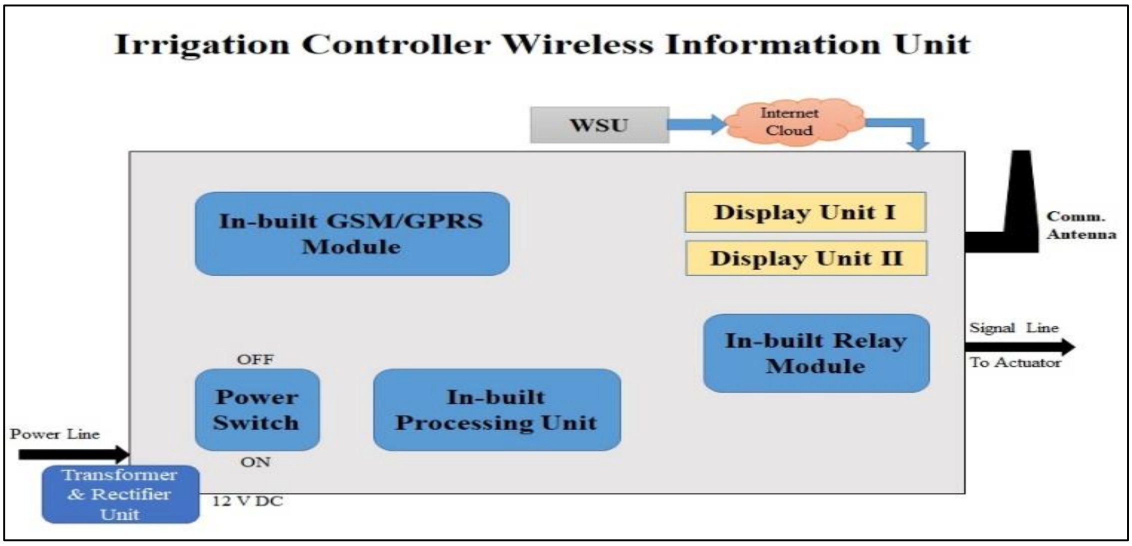

Fig 4: Schematic Front Panel Diagram of WIPU

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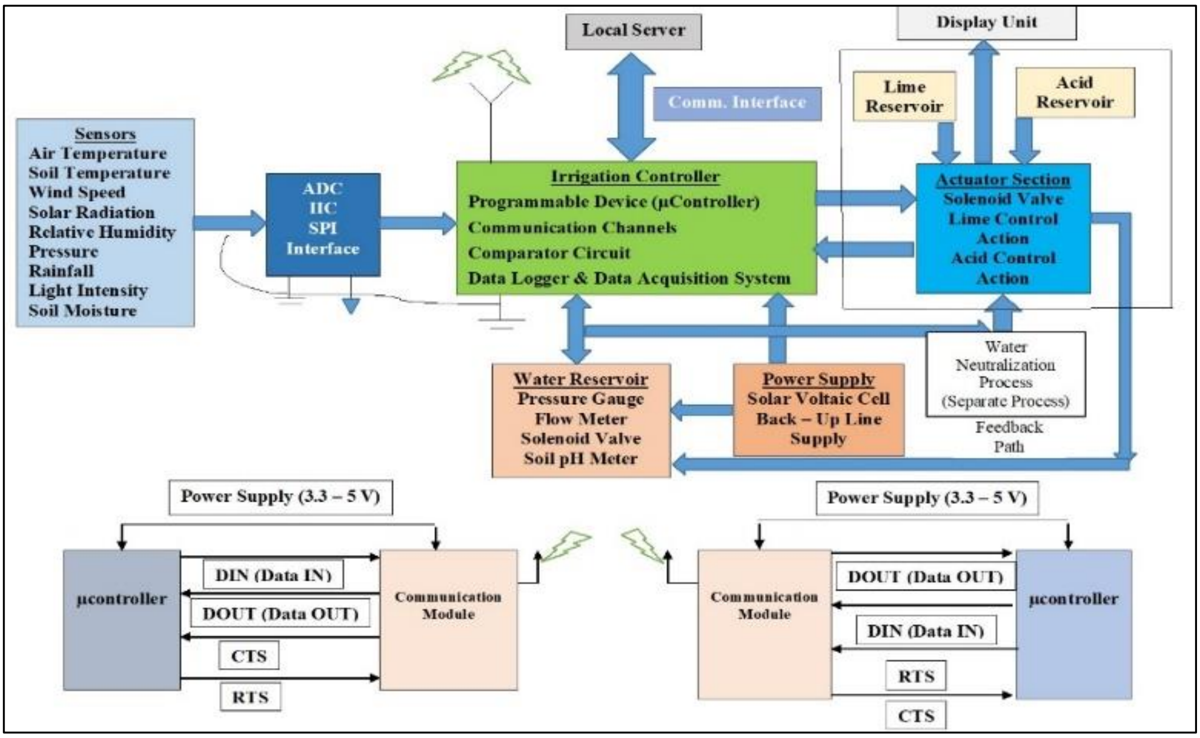

Fig. 5. System connection to the cloud network for data exchange

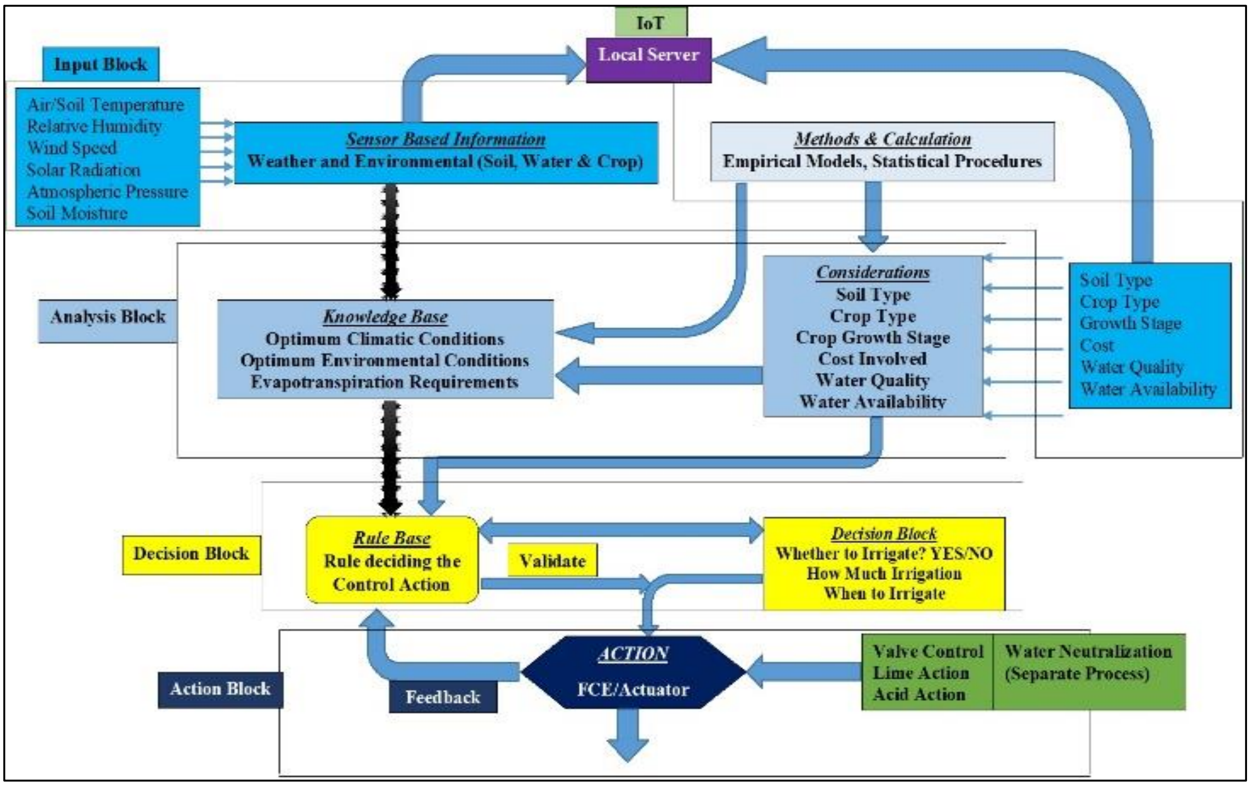

Fig 6: Block Descriptions of the SAIC

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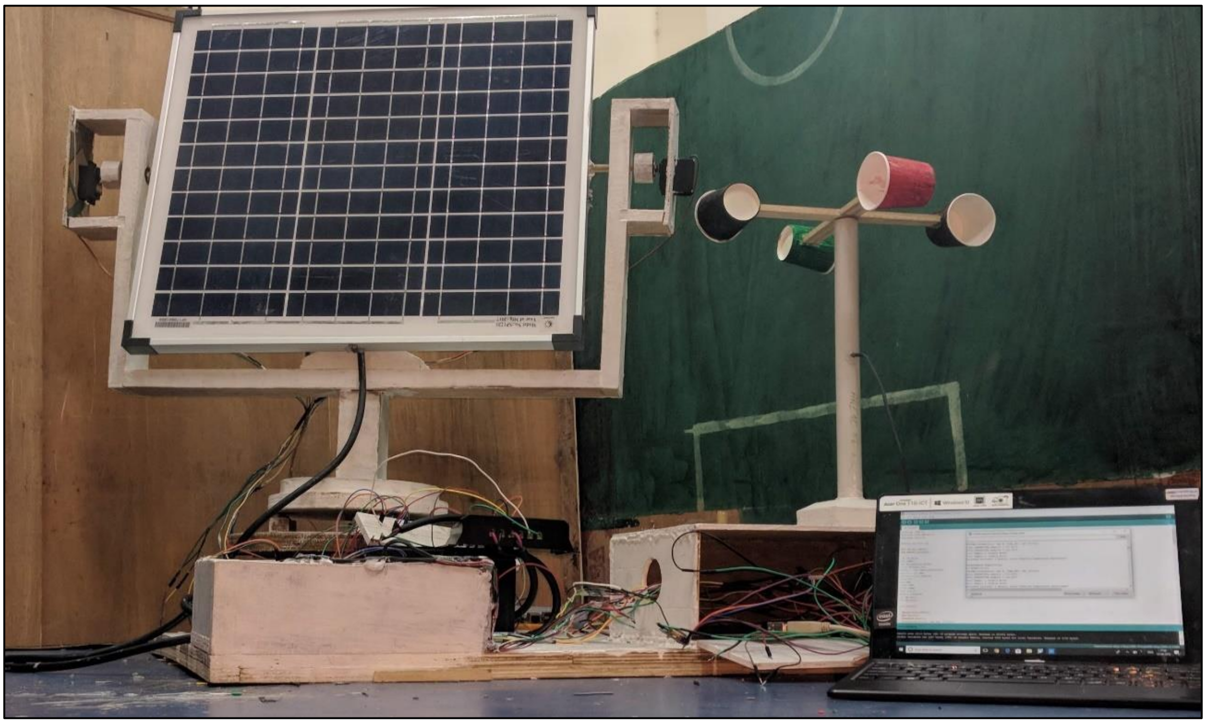

Fig 7. Stand-Alone Smart Weather Station

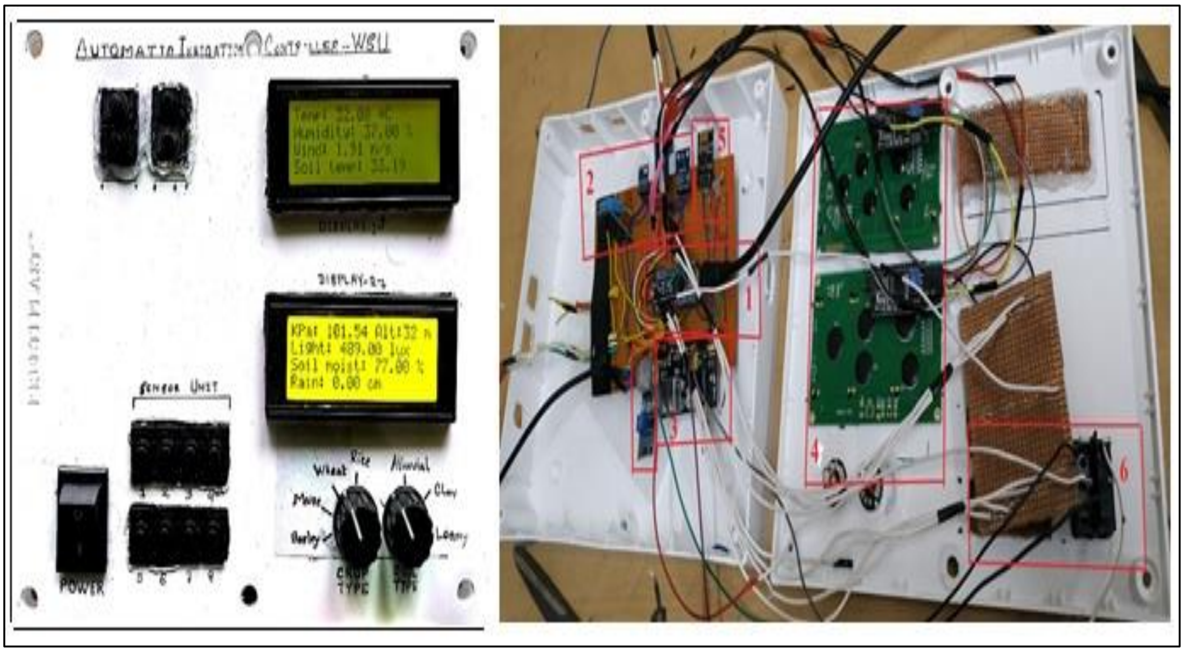

Fig 8: Internal Circuit Connection of the WSU

1 MCU; 2 Sensor Nodes; 3 Power Supply Unit; 4 Display Unit; 5 Wi-Fi Unit; 6 Power Switch & Switch Units

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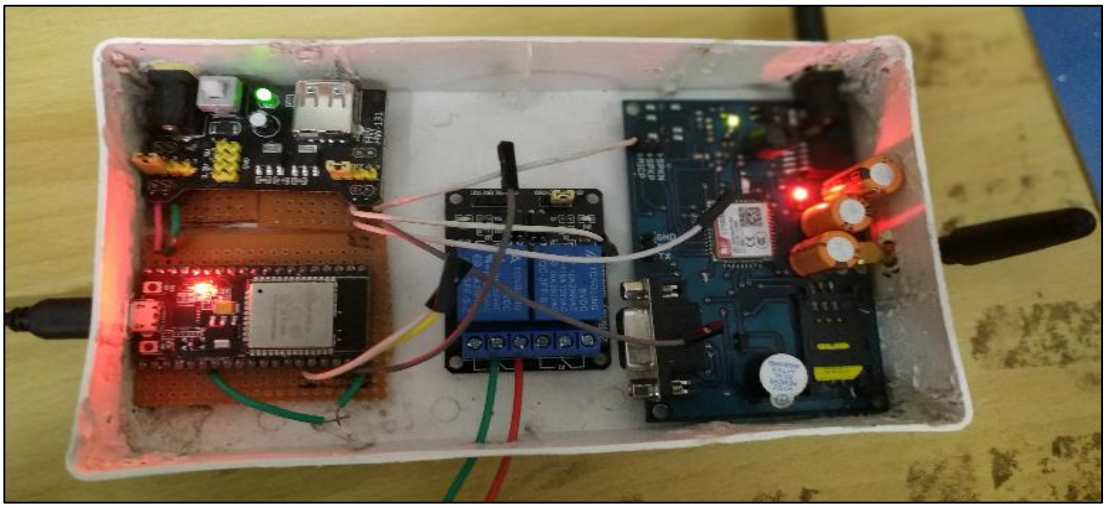

Fig 9: Internal Circuit Connection of the WIPU

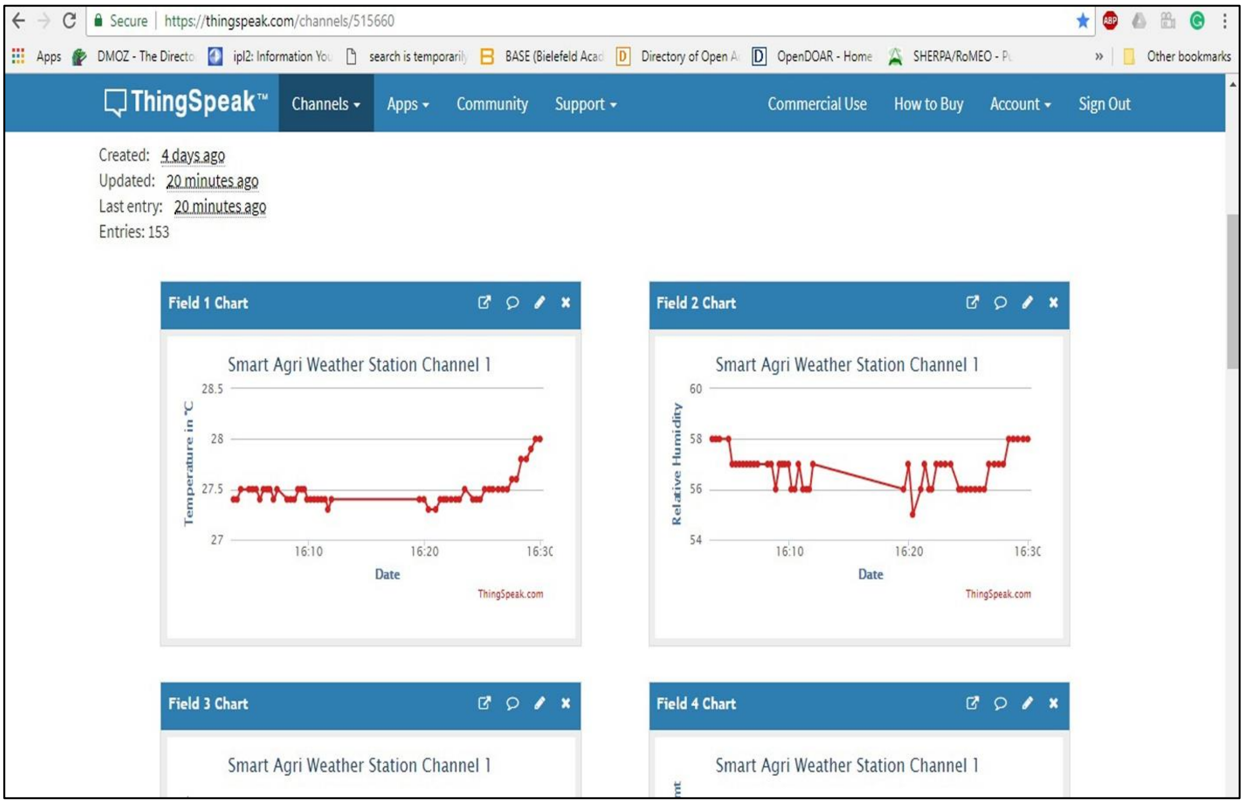

Fig 10. Data being uploaded to the cloud-server in ThingSpeak

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Table 1. Summary of Salient Features and Drawbacks of other model designs.

Research Team	**Salient Features & Drawbacks**
R. G. Allen et al. (1998)	• The principle concept and generalization and empirical modelling of evapotranspiration. • Time-based irrigation scheduling. • No sophisticated controller used.
K. S. Nemali et al. (2006)	• Developed solenoid valve based irrigation controller based on volumetric measurement. • Limited to Greenhouse-based nursery applications only. • Soil-moisture is the only determining factor.
S. A. O'Shaughnessy et al. (2010)	• Remote canopy temperature is used as set-point to trigger control action. • Did not consider evapotranspiration water loss. • Limited to cotton irrigation.
Zhang Feng et al. (2011)	• Introduced WSN and internet technology in data collection. • Did not use cloud server and cloud computation.
Jaoquin Gutierrez et al. (2014)	• Worked with WSN and duplex cellular-internet communication to automate irrigation. • Limited to Greenhouse application. • Factors like relative humidity, wind speed, and solar radiation are not considered to measure water-loss.
Jason Parmenter et al. (2014)	• WSN and cellular-connectivity used. • Web-based dynamics proposed. • Limited data storage capability.
Kim et al. (2008)	• Used distributed WSN. • Irrigation control based on direct reading with no control design.
Agbetuyi et al. (2016)	• Soil moisture based automatic irrigation system. • Stand-alone system without connection to any network. • Categorization of irrigation scheduling.
Tiberiu Marinescu et al. (2017)	• Compared PID, Fuzzy, decision support system (DSS) and model prediction control (MPC). • Limited to vineyard study. • Schematic untested model. • No data on efficiency.
Erean Avsar et al. (2018)	• Developed cloud-based automatic irrigation system. • Lysimeter based water-loss determination. • Wind speed and solar radiation data are not considered. • Limited to strawberry cultivation.
Usman et al. (2010)	• Showed promising results with limited capability based on the training function, hidden layers and learning rate. • The model is not tested physically and therefore not validated.
Our Improvement	• Requirement-based irrigation scheduling. • All related and relevant parameters viz. air and soil temperature, atmospheric pressure, soil moisture content, soil and water pH, altitude, solar radiation, wind speed, and relative humidity are taken into consideration. • Exhaustive rule-base to accommodate all possible combinations of soil-crop-growth stages. • Cloud server repository used for storage and access of look-up table and data. • We have validated our design with both simulation and field trial run, achieving significant improvements.

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Table 2. Water Level Requirement for Different Crop-Soil Combinations (cm)

Crop-Soil Combination	**Preparation Stage**	**Initial Stage**	**Crop Development Stage**	**Mid-Season Stage**	**Late-Season Stage**
Rice Clay	5	8	19	15	2
Rice Silty	6	9	21	17	2
Rice Loam	6	10	24	18	2
Rice Sandy	7	11	26	21	2
Wheat Clay	3	4	10	8	1
Wheat Silty	3	5	11	9	1
Wheat Loam	4	5	12	10	1
Wheat Sandy	4	6	13	11	1
Maize Clay	4	6	13	10	1.5
Maize Silty	4	6	14	11	1.5
Maize Loam	5	7	16	12	2
Maize Sandy	6	8	18	14	2
Barley Clay	3	4	10	8	1
Barley Silty	3	5	11	9	1
Barley Loam	4	5	12	10	1
Barley Sandy	4	6	13	11	1
Days	**8**	**20**	**30**	**30**	**40**

Table 3. List of Equipment used

Equipment	**Function**	**Type**	**Quantity**	**Location**
Temp. Sensor °C	Air temp. measurement	DHT22	5	WSU
Temp. Sensor °C	Soil temp. measurement	DS18B20	4	WSU
Humidity Sensor %	Relative Humidity	DHT22	5	WSU
Pressure Sensor	Atmospheric Pressure	BMP180	5	WSU
Moisture Level %	Soil Moisture Level	YL 69	4	WSU
Level Sensor cm	Standing Water	HC-SR04	4	Field
pH Sensor	Soil & Water pH	SEN0249 pH Probe	4	Field
Light Sensor Lux	Light Intensity	BH1750	5	Weather Station
Anemometer m/s	Wind Speed	Cup-type anemometer	1	Weather Station
Hall Sensor	Wind Speed	A3144 Hall Effect Sensor	1	Weather Station
Photovoltaic Panel	Solar Radiation	12V, 20W (45cm x 35cm)	1	Weather Station
Current Sensor A	Solar Radiation	ACS712	1	Weather Station
Voltage Sensor V	Solar Radiation	Generic	1	Weather Station
Controller	Control Operation	ATmega 328 SOC Nano	1	WSU
GSM/GPRS	Network communication	SIM 800C	1	WIPU
Wi-Fi	Wireless communication	NodeMCU ESP32	2	WSU & WIPU
Evaporimeter	ET water loss	Class A Pan lysimeter	1	Field
Display	Data monitoring	20X4 LCD	2	WSU
Water Pump	Water supply	1 HP 1-ϕ AC pump	1	Field

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Table 4. Characteristic features of the Sensors

Sensor	Range	Accuracy	Stability	Resolution.
Air Temp. Sensor DHT22 (°C)	-40 – 125	± 0.5 °C	±0.5 °C/year	0.1 °C
Soil Temp. Sensor DS18B20 (°C)	-50 – 125	± 0.5 °C	±0.5 °C/year	0.25°C
Humidity Sensor DHT22 (%)	0 – 100	± 2.5 %	± 0.5% RH/year	0.1 %
Atm. Pressure Sensor BMP180 (mbar)	300-1200	± 1 mbar	± 2	0.02
Soil Moisture Level YL-69 (%)	0 – 100	0.1 %	± 1	0.1 %
Level Sensor HC-SR04 (cm)	1 – 400	1 mm	Very High	3 mm
Soil & Water pH Sensor SEN0249	0-12	± 0.1	± 0.1	0.1
Lux Sensor BH1750	1 - 65535	± 0.5	Very High	0.5
Current Sensor ACS712 (A)	0 – 20	0.1 A	Very High	0.1 A
Voltage Sensor V	0 - 25	0.1 V	High	0.1 V

Table 5. Monthly Average Climatic Data for the Cultivation Period

Parameters	Nov	Dec	Jan	Feb	March
Air Temp (°C)	28.4	20.3	19.8	24.9	31.5
Soil Temp (°C)	33°C	31	26	29	34.5
Rel. Hum (%)	65	63	62	70	68
Solar Radiation (kWh/m^2/Day)	4.89	4.67	4.32	5.01	5.44
Wind Speed (km/h) (NE)	3	4	1	2	3
Rainfall (mm)	38	33	28	27	133
Atm. Pressure (mbar)	1014	1014	1015	1013	1013
WSU ET (mm)	2.89	2.23	2.01	2.52	3.17
Lysimeter ET (mm)	2.81	2.25	2.11	2.43	3.12
WSU-Lysimeter ET difference (%)	2.84	0.9 (-ve)	4.74 (-ve)	3.7	1.6

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Table 6. Comparison of Harvest between Season 2017 and 2018

Period	2017 (Period 10th November, 2017 – 1st April, 2018)	2018 (Period 10th November, 2017 – 31st March, 2018)
Crop Season:	Aman	Aman
Crop Type	Paddy (Rice)	Paddy (Rice)
Farm Size	1 Acre (61X66 m^2)	1 Acre (61X66 m^2)
Cultivation Period	141 Days (fallow to harvest)	140 Days (fallow to harvest)
Rainfall received	740 cm	770 cm
Water pH	Varied between 6.5 and 7.5 (Optimum)	Varied between 6.5 and 7.5 (Optimum)
Soil pH	Varied between 6.9 and 7.6 (Optimum)	Varied between 6.9 and 7.7 (Optimum)
Water supplied	7.2 million litres	5.56 million litres
Water Usage %		27% less water used
Crop Harvest	2.21 Tons	3.10 Tons
Harvest % Improvement	-	40% increase in harvest.
Water/ kg rice	3269 litres/kg	1795 litres/kg