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Optimized power and water allocation in smart irrigation systems

Wid Badee Abdulaziz[1], Muayad Sadik Croock[2]
[1]Computer Engineering Department, University of Technology-Iraq, Iraq
[2]Control and Systems Engineering Department, University of Technology-Iraq, Iraq

ABSTRACT

Agriculture has a significant role in countries' economy, but irrigation process consumes both power and water resources. Since in agriculture the goal is to maximize crop's yields with minimize costs, it is important to design a national smart irrigation system with optimal allocation of power and water resources especially in a plantation area with little rains. In this work, an optimized on-demand smart irrigation system is proposed to manage the allocation of the consumed power and water in agriculture field. The system controls irrigation process by utilizing Wireless Sensor Network (WSN) to collect real-time data from the field using sensors. Raspberry pi takes appropriate decision about irrigation process according to received data from sensor nodes, and commands are sent from it to actuator nodes. Secured Message Queuing Telemetry Transport (MQTT) protocol with Transport Layer Security (TLS) authentication protocol is used in managing the data exchange in the network over Wi-Fi technology. In addition, an optimal power and water consumptions formula is derived using Lagrange Multiplier method to allocate resources in an optimal way depending on watering demands. Both theoretical and practical results approve the efficiency of the proposed system in managing irrigation process optimally.

Keywords: Optimization, Lagrange Multiplier, TLS, WSN, Irrigation System

Corresponding Author:

Wid Badee Abdulaziz
Computer Engineering Department
University of Technology-Iraq
Baghdad, Iraq
E-mail: ce.19.16@grad.uotechnology.edu.iq

1. Introduction

Nowadays, designing an optimal irrigation system is a crucial issue in agriculture field, due to water scarcity problem with the increase in population around the world. So, to manage irrigation system, new technologies are integrated to optimize water and power consumption besides reducing efforts [1][2][3]. Wireless Sensor Networks (WSNs) have a significant role in agriculture and other applications due to its flexibility and ability of processing data in different environments with an easy programming[4][5][6] . The use of sensors in recent applications is not limited to environmental sensing, but also collecting data from the field and sending information to users depending on some situations [7]. Recently, researchers proposed many studies to design an irrigation system with optimal allocation of water and/or power resources while maintaining good yields quality. Authors in [3] proposed an automatic irrigation system that relies on both field and crop data to guess water needs. This was done using the Evapotranspiration calculation and turned on the system at minimal cost to achieve optimal energy and water use. In [8], the authors suggested a new multi-agent system (MAS) to get an automated monitoring and controlled irrigation system for potato crops. MAS was developed using a cloud computing platform which can collect information from WSNs to define factors and determine irrigation requirements. This smart system has the potential to keep resources and upgrade the efficiency of crop production systems, specially in rustic areas. The intelligent irrigation system shown in [9]was developed to decrease water consumption by combining IOT, cloud computing, and optimization techniques. The used optimization model minimizes the consumed water efficiently. The efficiency of the suggested approach, which minimizes irrigation water use, was proven by a comparison of the recommended optimization-based control model with the flow-based control model. In [10], a multi-objective optimization method using an intelligent irrigation system was introduced to reduce the energy cost of operating two water pumps that maintain the water required for farm's irrigation. It was significant to obsereve that the genetic algorithm was used to get the optimal solution. To achieve optimal water consumption, the authors of [11] suggested integrating the automated irrigation system with an accumulative neural network (ANN). The suggested system was simulated using the MATLAB Toolbox of Neural Network with feed-forward backpropagation ANN model. In addition, in [12], the author suggested an approach for designing WSN-based automated irrigation systems. All sensor nodes collect data on an ongoing basis. However, just data with a recurrent timer is sent to the base station or data that exceeds the threshold. To reduce the node's power consumption for each transmission, fuzzy logic was utilized to locate the entire cluster head in the existing round.. Comparisons with other routing protocols have shown that it effectively minimizes power consumption at each transmission and extends the life of the entire network. In [13], a WSN-based intelligent irrigation system with optimal consumed power using the Lagrange multiplier method was suggested. The aim was to partition power optimally and efficiently, while optimally minimizing power and watering, depending on the plant's watering needs and watering time. In this work, an optimized smart irrigation system based on WSN is proposed. Two sensor nodes are used as a prototype to gather crop's watering status and send these real-time data to Raspberry pi using Wi-Fi and secured MQTT protocol to optimize the right decision about starting or stopping irrigation process. The Raspberry pi decides the quantity of water required to irrigate the plant based on climatic situation, which leads to consume power. Moreover, an optimal power and water equations are derived using Lagrange multiplier and implemented in Raspberry pi to get an optimal allocation of water and power resources depending on water demands. As a case study, tomato crop is used to verify the proposed system operation and the obtained results in simulation and real-time systems prove the claim of saving more power and water.

2. Poposed optimal irrigation system

In this section, the suggested optimal irrigation system is demonstrated with two sub-sections: problem formulation and structure of the proposed smart irrigation system

2.1. Problem formulation

The primary purpose of this research is to reduce the amount of power and water used in the irrigation process. To derive problem's mathematical formulation, Lagrange multiplier method is utilized. The mathematical formula, used in [13], is developed to add water constraints in addition to power constraints. The proposed mathematical formula is:

$$\boldsymbol{E} = \sum_i \boldsymbol{k}\, \boldsymbol{d_{ni}}\, \boldsymbol{p_i} \qquad (\mathbf{1})$$

where ***E***: is the system's overall energy consumption, ***Pi***: is the i-th irrigation line's power consumption, ***dni*** is the i-th irrigation line's net irrigation consumption [*mm*], and ***k*** is:

$$\boldsymbol{k} = \begin{cases} \mathbf{1}/(\boldsymbol{q} \times \boldsymbol{N} \times \boldsymbol{E} & \boldsymbol{for\ drip} \\ \mathbf{1}/\boldsymbol{lb} \times \boldsymbol{E} & \boldsymbol{for\ sprinkler} \end{cases}$$

Where ***q*** is the rate of discharge of emitter [*l/s*], ***N*** is the total number of emitters, ***E*** is the efficiency of field application that depending on the watering technique, and ***Ib*** is basic sprinkler infiltration rate [*mm/sec*]. So, to minimize equation (1) using Lagrange multiplier method, the function should be updated to convex or concave. This is accomplished by using the exponential function on both sides of the equation. The objective function is:

Minimize: $$\boldsymbol{exp^{E}} = \boldsymbol{exp^{\sum_i K\, dni\, Pi}} \qquad (\mathbf{2})$$

Subject to:

$$\sum_i \boldsymbol{P_i} \le \boldsymbol{PT} \qquad (\mathbf{3})$$

$$\sum_i \boldsymbol{d_{ni}} \le \boldsymbol{ETc} \qquad (\mathbf{4})$$

Where ***PT*** is the total consumed power, and ***ETc*** is total crop evapotranspiration which is measured in millimeters per day and indicates the total amount of irrigated water necessary for crop development.

The optimal power and water equations obtained after applying Lagrange Multiplier method for each irrigation line in the field are:

$$P_i = \frac{d_{ni} \times PT}{\sum_i d_{ni}} \quad , \qquad (5)$$

and

$$d_{ni} = \frac{P_i \times ETc}{\sum_i P_i} \qquad (6)$$

2.2. Proposed smart irrigation system structure

In this work, control and management of irrigation process are done using a structured WSN that includes sensors and actuators. Two sensor nodes and one Raspberry pi are used to implement a prototype of the proposed system. Each sensor node gathers watering status using two types of sensors: soil moisture sensor and temperature sensor. These sensors are connected to ESP8266 microcontroller which reads the sensors' real-time data and sends it to Raspberry pi using WiFi and MQTT protocol that is secured with TLS authentication protocol. At Raspberry pi, the received sensors' reading are checked to decide about start irrigation process or not depending on both plant's and soil's features. If the decision is to start irrigation process, the Raspberry pi sends power on command using WiFi technology and MQTT protocol to the controller to power on motors that connected on it. At the same time, the Raspberry pi does many calculations to manage irrigation scheduling. The required amount of water in irrigation process is also estimated by Raspberry pi using crop's evapotranspiration equation [13] [14][15] and [16]:

$$ETc = ETo \times Kc \qquad (7)$$

where, ETc is the crop water requirements [mm day−1], $ET0$ is the reference evapotranspiration [mm day−1], and Kc is the crop coefficient. The net irrigation amount d_n is estimated by[17][18]:

$$d_n = (\theta_{FC} - \theta_{Cm}) \times Z_r \qquad (8)$$

where, d_n is the existing amount of net irrigation [mm], θ_{FC} is the amount of water at field capacity [m3 m-3], θ_{Cm} is the soil moisture level at this moment [m3 m-3], and Zr is the depth of rooting [m]. For optimal allocation of power resources, an optimal power equation (5) is used to estimate the consumed power according to the required amount of water. In this manner, motors at lines that need more amount of water will consume more power to increase its flow rate and reduce irrigation application time. At contrast, motors at lines need little amount of irrigation will consume little power to reduce its flow rate and increase its irrigation time. As a result, the irrigation system will shut down at the same time without exceeding the value of the total power consumption before optimization. On the other hand, the water resources are allocated optimally using equation (6) that derived by Lagrange multiplier method to irrigate plants without exceeding the total amount of water required by plants to assure good quality crops with optimal conumption of resources. Moreover, irrigation application time is estimated according to the optimal irrigation water by this equation [18].

$$T = \begin{cases} d_n(optimal) / (q \times N \times E & for\ drip \\ d_n(optimal) / lb \times E & for\ sprinkler \end{cases} \qquad (9)$$

All the estimated values from this calculations which are needed to manage irrigation process is sent from Raspberry pi to ESP8266 nodes with the aid of WiFi technology and MQTT protocol. The flow chart of the proposed system is shown in Fig. (1). The work flow of the proposed algorithm can be explained in the following steps:

1. After powering ON the system, ESP8266 microcontroller reads sensors values.
2. Checking TLS certificate authority to send sensors readings to MQTT broker. If the certificate verified, ESP8266 sends data to Raspberry pi using Wi-Fi technology and MQTT protocol. At the other hand, if certificate verification failed, no data is sent to Raspberry pi and the work returns to the beginning.
3. The Raspberry pi, as a base station in the system, is responsible of making irrigation decision and scheduling process. So, it receives sensors reading, sends it to server for monitoring using Node-RED tool.
4. The Raspberry pi makes the necessary calculations to estimate crop water requirements using equations (7) and (8) as well as estimating optimal power and water consumption using equations (5) and (6) respectively. The applicate irrigation time is calculated according to optimal power and water values, while the microcontroller continues reading sensors at the same time.

5. The decision of starting irrigation or not depends on soil moisture sensor reading. If the reading below a preferred threshold value for a particular crop, then irrigation is started by sending power on command from Raspberry pi to ESP8266 to power on water pump for a specific time with a continuous check of soil moisture value to avoid over irrigation that harms plant growth and crop production. When sensor reading is above the determined threshold value or irrigation run time ends, Raspberry pi sends power off command to ESP8266 to stop water pump and starts the operation again.

A prototype is suggested to implement the proposed optimal irrigation system with the following hardware components:

- ✓ Laptop
- ✓ Raspberry pi 4 Model B[19]
- ✓ ESP8266 microcontroller [20]
- ✓ FC-28 soil moisture sensor [18]
- ✓ DS18B20 temperature sensor [21]
- ✓ Light Emitting Diodes (LEDs)
- ✓ 15-ohm resistors.

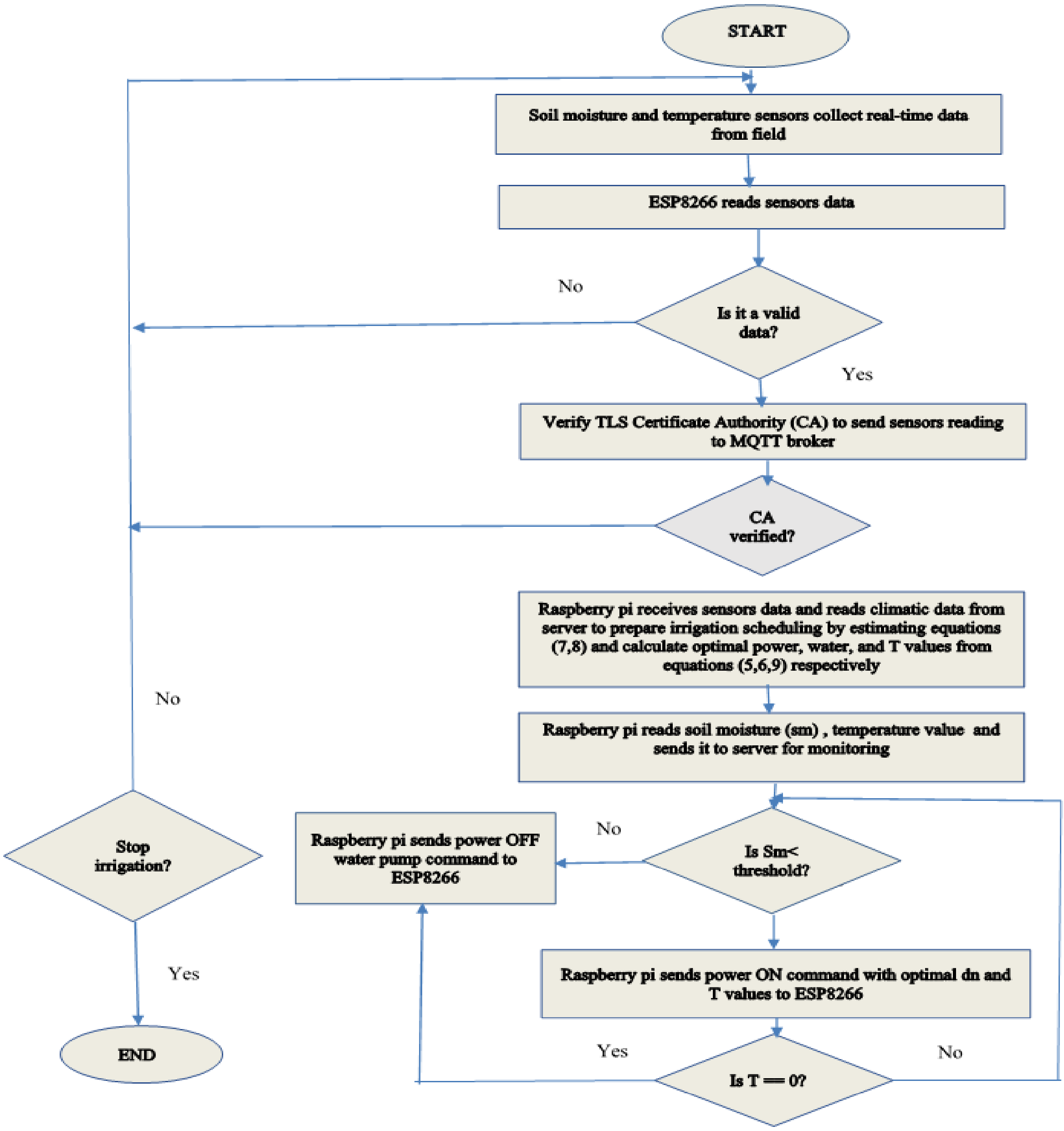


Figure 1. Flow chart of the proposed system

Figure 2 shows the block diagram of the hardware components structure. It is clearly shown that the components are connected together throughout the main control unit, which is Raspberry pi4 that collects the data from the node controller (ESP8266).

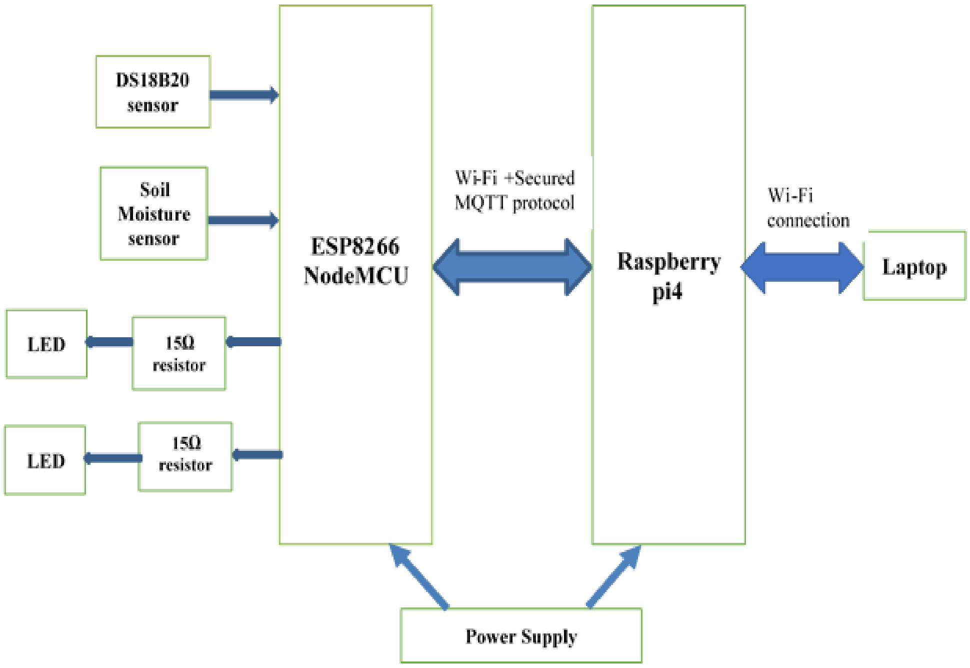


Figure 2. Block diagram of the proposed system

3. Results and discussion

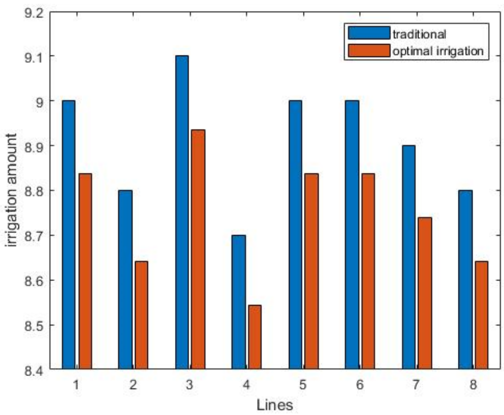
Due to the high variance of irrigation factors of different plants, tomato crop is chosen as a case study to test and verify the proposed system operation. Tomato crop has 4 development stages with 90-150 total days: initial, crop development, mid-season, and late season. Every stage has different water requirements related to climate and crop coefficients change [15]. The selected planting region is Baghdad, the soil type in Baghdad is loam, which is preferred for tomato planting and the suitable soil moisture percentage is 70-80% [15], and [22]. Moreover, the best irrigation strategy for tomato is drip irrigation. The reference evapotranspiration (ET_0) is estimated by CLIMWAT software. Assuming tomato crop is in mid-season development stage, theoretical and practical implementation of the proposed system are done to verify its validity and efficiency.

3.1. Theoretical results

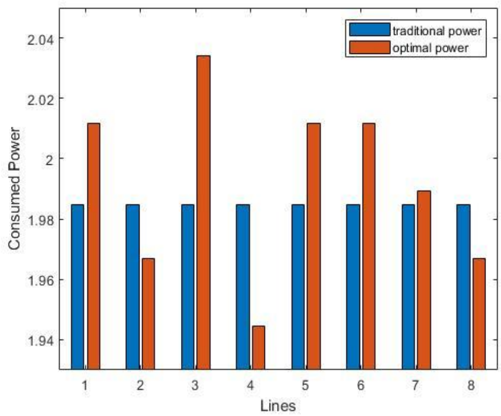
In order to verify the proposed optimal strategy, MATLAB software is used. Assuming an irrigation system with 10^{th} irrigation lines, tomato crop total water requitements is determined using equation (7) to estimate water constraints that is equal to (87.2 mm) and the consumed power is considered from [13]. Table 1 shows results that confirm the functionality of the proposed model in allocating power resources optimally depending on watering demands using equation (5). In the suggested model, motors on lines that need more irrigation amount can get more power than motors on lines with little watering demands to increase motor's flow rate and as a result, the irrigation time can be minimized to reduce system's operation time. Additionally, the consumed water is re-allocated using optimal power value and equation (6) to ensure optimal water consumption by maintaining water constraint. Figure 3 shows the simulation results in MATLAB software. From Table 1 and Figure 3, it is shown that the proposed algorithm allocates the available power and irrigation water among the lines in optimal way, in which the thresholds, which are the initial values of power and water, are guaranteed not to be crossed. At the other hand, the consumed water is reduced by (dni=1.6 mm). The reduction in water consumption approves the desired improvement proposed in this work to the model in [13], since the latter suggested an optimal allocation of power resources without affecting water resources.

Table 1. Consumed power and water for tomato crop

Line no.	Initial power (KW)	Assumed d_{ni} (mm)	Optimal power (KW)	Optimal d_{ni} (mm)
1	1.98474	9	2.0116	8.8378
2	1.98474	8.8	1.9669	8.6414
3	1.98474	9.1	2.0339	8.9360
4	1.98474	8.7	1.9445	8.5432
5	1.98474	9	2.0116	8.8378
6	1.98474	9	2.0116	8.8378
7	1.98474	8.9	1.9892	8.7396
8	1.98474	8.8	1.9669	8.6414
9	1.98474	8.8	1.9669	8.6414
10	1.98474	8.7	1.9445	8.5432
Total	19.8474	88.8	19.8474	87.2000



a. Water Consumption



b. Power Consumption

Figure 3. Consumed water and power for 8 lines of tomato crop

3.2. Practical results

The proposed system is implemented in hardware using WSN. As a prototype, two sensor nodes and Raspberry pi are used to verify the operation of the suggested optimal strategy in practical. A fair allocation of power resources before optimization is assumed to be 3KW for each node. Tomato crop has four development stages with 90-150 total days: initial, crop development, mid-season, and late season. Each stage has different water requirements relating to climate and crop coefficient data. Assuming planting is started on October, the total water requirements for all stages in order (6.096, 4.878, 3.496, 4.698 mm). These values are estimated in Raspberry pi using equation (7). Optimal power and water consumptions are calculated in Raspberry pi according to the proposed formula in equation (5) and (6) respectively. Table 2 shows assumed power and net irrigation values against the results optained from Raspberry pi calculations for two lines. The obtained results verify the operation of the proposed optimal strategy in allocating power resources depending on water demands. So it delivers more power to motors on lines that need more irrigation amount and little power to other motors with lines need little watering demands, while maintaining the total consumed power not change. Moreover, allocating water resources optimally using optimal power value with maintaining water constraints

is also verified. It is important to note that the consumed water is reduced by (d_{ni}=0.1-1.2 mm). In the proposed prototype, the optimal irrigation time is computed according to equation (9). In this manner, when Raspberry pi decides to start irrigation according to sensors readings, it sends power ON command to ESP8266 microcontroller using Wi-Fi technology and MQTT protocol to power on LEDs for a specific time equals to optimal irrigation time. When this time is elapsed, Raspberry pi sends power OFF command to ESP8266 to power off LEDs while the latter continues in reading sensors and sending real-time readings to Raspberry pi.
To estimate optimal irrigaion time, the water pumps flow rate of each motor must be detemined according to the new optimal power values. This is done in Raspberry pi with python programming language using the following equations [23].

$$\boldsymbol{P} \propto \boldsymbol{N}^3 \qquad (\mathbf{10})$$

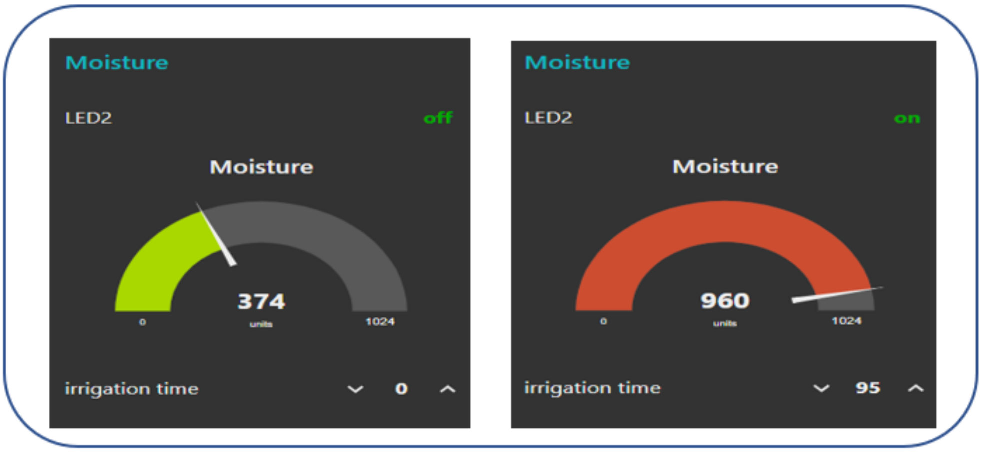
$$\boldsymbol{Q} \propto \boldsymbol{N} \qquad (\mathbf{11})$$

Where $\boldsymbol{P}$ is pump power (kw), $\boldsymbol{N}$ is speed of pump (rpm), and $\boldsymbol{Q}$ is pump flow rate (gpm or lt/h).
In order to monitor system operation, Node-RED dashboards are used as shown in Fig. (4). The soil moisture dashboard displays sensor readings with required decision from Raspberry pi. The sensor readings range is between 0 and 1024, with 0 reading represents 100% moisture value and 1024 reading represents 0% moisture value. As mentioned earlier, the preferred soil moisture value to tomato crop is 70-80%, this is equal to 430 in the sensor's reading. So, if soil moisture sensor reading is above 430, the Raspberry pi sends power ON command to ESP8266 to power on LEDs (start irrigation process) to a specific time equals to the estimated irrigation time after applying power and water optimization values. At the other hand, when soil moisture sensor reading is below 430 (more than 70%), Raspberry pi sends power OFF command to ESP8266 to power off LEDs (stop irrigation process). From Raspberry pi calculations after implementing power and water optimization formula, the application irrigation time of node1 and node2 are 100 and 99 seconds respectively that is approximately equal. This approved that the proposed optimal strategy is valid and efficient in allocating power and water resources to nodes with different water requirements to save power and water consumption.

Table 2. Practical Consumed Power and Water for Tomato Crop

Development stage	**Line no.**	**Initial power (KW)**	**Assumed d_{ni} (mm)**	**Optimal power (KW)**	**Optimal d_{ni} (mm)**
Initial	1	3	3.1	2.9524	2.9196
	2	3	3.2	3.0476	3.0964
	Total	6	6.3	6	6.0960
Crop Development	1	3	2.5	3.0303	2.4636
	2	3	2.45	2.9697	2.4144
	Total	6	4.95	6	4.8780
Mid-Season	1	3	1.8	3.0423	1.7726
	2	3	1.75	2.9577	1.7234
	Total	6	3.55	6	3.4960
Late	1	3	2.35	2.9685	2.3243
	2	3	2.4	3.0315	2.3737

	Total	6	4.75	6	4.698



a. Line1

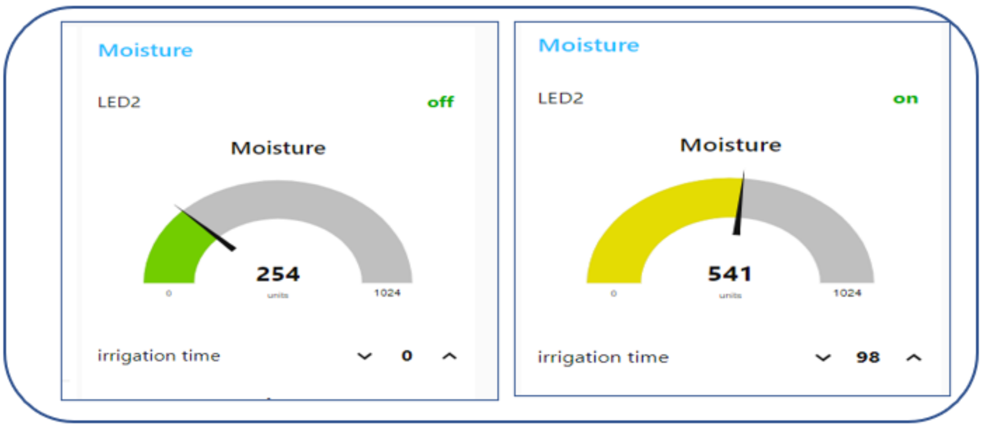


Figure 4. Node-RED monitoring dashboard

4. Conclusions

In this work, an optimal-smart irrigation system is proposed to help in managing the power and water consumptions problem in irrigation process. The suggested system is implemented with the aid of WSNs technology. The problem is formulated mathematically using Lagrange Multiplier method to obtain optimal power and water consumption formulas which is tested with MATLAB software to approve its operation theoretically. Additionally, a hardware prototype is proposed and tested to verify system operation in practical. Since the suggested system is aspired to be a national irrigation system, authentication is required to assure sensor nodes identity. So, a secured MQTT protocol with TLS authentication protocol are used to exchange data between sensor nodes and Raspberry pi. Theoretical and practical results approved the operation of the proposed system in allocating power and water resources optimally depending on irrigation demand to reduce the consumed power and water in irrigation process while maintaining good quality yields.

Declaration of competing interest

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

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