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ORIGINAL RESEARCH ARTICLE

Development and evaluation of smart irrigation system to enhance the water use efficiency

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ABSTRACT

For this purpose, a moisture sensor device was designed and constructed in February and March 2019 to determine the appropriate time to stop irrigation in furrow irrigation. Testing the device in the laboratory and its application in the Farm of the Campus of Agriculture and Natural Resources, University of Tehran (Mohammad Shahr), Iran, from April to July 2019. The purpose of this study was to evaluate the performance of a smart sensor of soil moisture to determine the optimum depth of installation and recording of soil moisture at 10, 30, and 50 cm depths and different length ratios in furrow irrigation. Initially, calibration of the device was carried out on field soil, and based on the obtained validation, the device was transferred to the field. To achieve the goals of optimum depth of installation and optimum length, 36-meter furrows with a distance of 0.75 m were created in the field. Sensitive lengths in furrows with 0.5 L, 0.75 L, and 0.85 L ratios were selected as the starting points. The results showed that in the calibration and validation phases, the R^2 values were 0.93 and 0.95, respectively, and in the calibration and validation stages, the value of nRMSE was 80 and 13.81%, indicating good model training in the calibration stage. Also, the average RE parameter in estimating soil moisture was 2.74%, indicating the high accuracy of the device in estimating soil moisture. The results also showed that if the device was installed at a depth of 30 cm from the soil surface of the furrow and at 75% from the beginning of the field, the depth and runoff losses would be minimal and irrigation adequacy would be best compared to other depths and lengths. It is expected that with optimal water consumption and timely interruption of irrigation, deep losses and runoff will be avoided, and with low water consumption, the productivity of crops will increase.

Keywords: surface irrigation; deep percolation; sensor; smart irrigation; calibration and validation

1. Introduction

Due to the problems of water scarcity and drought in Iran, proper and optimal water management and consumption are necessary. Water management requires policy-making to use water properly and efficiently, and a smart irrigation system is a suitable approach to using water properly[1–6]. Statistics show that about 80%–90% of Iran's water consumption is consumed in the agricultural sector, and therefore, special attention is needed in the irrigated agriculture sector[7,8]. Therefore, to monitor soil moisture and smartly control water

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consumption, the use of soil moisture sensors is essential[9–12]. Due to the import and high cost of smart control systems, Iranian farmers' use of this technology in irrigation systems has been limited. The purpose of this research is to use a cheap, inexpensive, and smart moisture sensor to determine the time of disconnection and connection of irrigation in the surface and traditional irrigation systems and to evaluate their efficiency. But the important question is: where is the right place to install the sensor? Therefore, one of the other objectives of this study is to determine the optimal distance and depth of moisture sensor installation in furrow irrigation to warn of irrigation cut-off in different soils to achieve maximum efficiency and minimum losses based on discharge and furrow characteristics.

1.1. Optimal installation distance

In surface irrigation and especially furrow irrigation, finding the optimal distance from the beginning of the furrow to install the sensor is one of the most important processes necessary to minimize runoff losses, minimize deep percolation and plant water requirements, and maximize irrigation efficiency. The optimal installation distance of the sensor is where the depth losses and runoff are minimal and the water supply and efficiency have their maximum value.

1.2. Optimal installation depth

According to the vertical front of the advance and redistribution of moisture (continuation of the progress of the wet front after the discharge), the optimal depth of sensor installation in the soil is determined. The moisture sensor should be installed above the depth of root development as much as the redistribution of moisture to minimize deep losses along the furrow.

1.3. Hypothesis and necessity of conducting research

In irrigated lands in Iran and around the world, about 90% are irrigated by surface irrigation and 10% by pressurized irrigation, which can be automated. Due to the multiplicity of surface irrigation fields and, on the other hand, the existence of high water losses like this system, it is necessary to study and evaluate the use of smart irrigation to minimize losses, increase efficiency, and improve water use efficiency. In traditional agriculture, the farmer disconnects and connects irrigation water based on experience and objective observations, which isn't usually appropriate in terms of time and results in irrigation losses. The most important advantage of a smart irrigation system is its optimal use of water. In addition, the farmer can easily irrigate his farmland regularly and accurately at any time and place. This research will be examined based on the following hypotheses:

- Deep percolation and runoff losses in surface irrigation (especially furrow irrigation) are high, and a smart irrigation system will be able to control them.
- There is no exact time of discharge cut-off in furrow irrigation, and it is based on experience that the built-in sensor eliminates this defect.
- In the sensors manufactured and available on the market, the optimal depth and optimal installation distance of the sensors are not known, which will be determined in this research in these two cases.

2. Materials and methods

2.1. Field experiment

The present study was conducted in the spring of 2019 on the research farm of the College of Agriculture and Natural Resources, University of Tehran, with loam texture and on a furrow irrigation system. A plot of land with dimensions of 4 m × 36 m was selected, and after selecting the desired plot, plowing and disc operations were performed to improve soil structure and remove weeds. Five furrows were created using grooves. The length of the furrows was 36 m, and the distance between the V-shaped furrows was 75 cm (the distance between the two ridges). To measure the inlet flow, a volumetric meter was installed at the beginning of the irrigation furrows, and the inflow was considered constant for all furrows. Before the start of the experiment, the first and second irrigations were done evenly between the furrows to equalize the soil conditions. A moisture sensor was installed in subsequent irrigations to reduce the error rate (**Figure 1**).

Figure 1. Preparation of furrows and pre-irrigation before the start of the experiment.

Regarding soil and water characteristics, it should be said that the average amount of soil acidity from zero to 60 cm was equal to 7.68, and the average salinity of soil-saturated extract at the mentioned depth was equal to 2.06 dS/m. Irrigation water quality is also based on the classification of the American soil salinity laboratory in class C1S1. By analyzing a sample of water in the laboratory, the electrical conductivity (EC) was equal to 0.68 dS/m and the pH was 7.13. The results of other physical properties of soil at different depths are given in **Table 1**.

Table 1. Physical properties of soil in the experimental farm.

Depths (cm)	Soil-forming particles (%)			Soil texture	P_b (g/cm^3)	θ_{FC} (g/g)	θ_{PWP} (g/g)	θ_S (cm^3/cm^3)
	Clay	Silt	Sand					
0–20	20.94	46.52	32.54	loam	1.37	27.24	14.88	46.27
20–40	24.70	42.54	32.76	loam	1.36	25.68	14.04	46.67
40–60	23.44	42.57	33.99	loam	1.36	23.49	12.92	46.67

P_b is the bulk density, θ_{FC} is the field capacity moisture, θ_{PWP} is the wilting point moisture and θ_S is the saturation moisture.

2.2. Construction of sensor or irrigation cut-off warning device (MRICAD[1])

There are four switches and warning lights to display the soil moisture that is transmitted to the monitor/data logger through the sensors. This device can record the moisture of three points from the depths of the soil or three points on the soil surface, and when the light related to each of these sensors is turned on, it will indicate the change and record the moisture related to that point. Soil moisture is displayed separately and as an average, and three keys are assigned to display the moisture of each point. An image of the built-in device (MRICAD) is shown in **Figure 2**.

[1] Moisture Record and Irrigation Cut-off Alarm Device

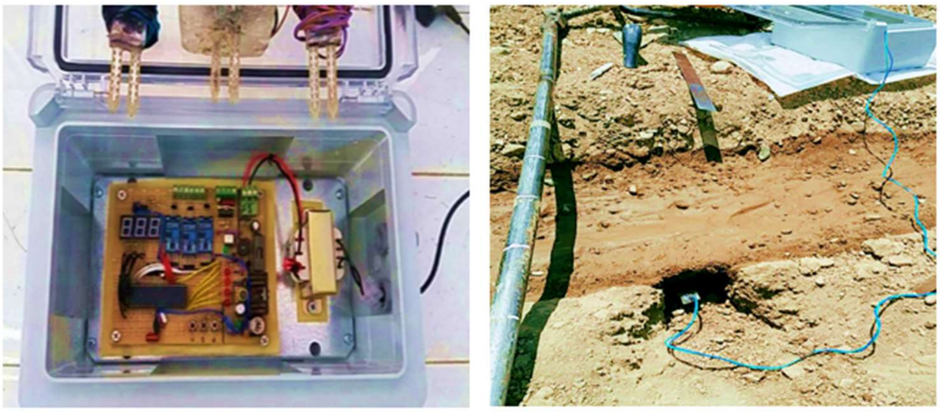

Figure 2. Image of MRICAD device with its three sensors.

This system consists of two main parts: hardware and software. The protection network, communication network, ground-based sensors, and display are components of the intelligent irrigation system. By changing the amount of soil moisture, the electrical resistance will change, and soil moisture will be measured based on it. Irrigation cut-off warning near-saturated moisture is what agriculture needs, and a resistance sensor has this capability. Finally, to calibrate and verify the device, the numbers read from the MRICAD device were compared with the measured real moisture, and the indices of Relative Error (RE), normal Root Mean Square Error (nRMSE), and Coefficient of Determination (R^2) were used. Due to page limitations, results are not provided.

3. Results and discussion

On the farm, to achieve the goals of the optimal installation depth of the device and its optimal distance, 36-meter furrows with a distance of 0.75 m were created. Sensitive distances in furrows with a ratio of 50%, 75%, and 85% from the beginning of the furrows, were selected as indicator points. The distances studied include:

- Control furrow and installation of the device at the end of the furrow, i.e., 36 m (CF),
- Install the device in 50% of the length of the furrow, i.e., 18 m (F1),
- Install the device in 75% of the length of the furrow, i.e., 27 m (F2),
- Install the device in 85% of the length of the furrow, i.e., 30.6 m (F3).

The MRICAD device was installed at the specified points on the edge of the ridge and at a depth less than the depth of root development. **Figure 3** shows the location of the device, the moisture sensor, the dimensions of the furrow, and the depth of soil sampling. According to the calibration and verification, the warning limit of the device was set on MAD equal to 65%, which was equivalent to saturated moisture with a constant volume of water for all furrows, and after turning on the warning light, the irrigation was cut off. Thus, the time and volume of water were recorded.

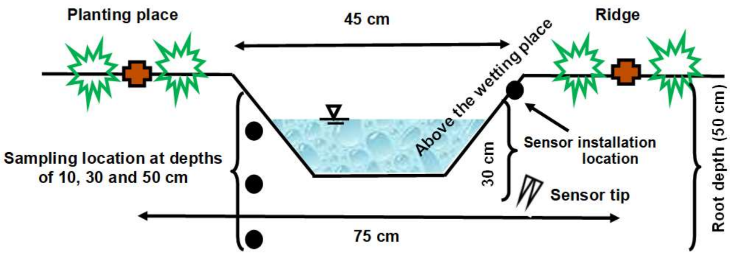

Figure 3. Location of the device, sensor and soil sampling.

According to Equation (1), the optimal installation depth of the device sensors will be obtained:

$$Y = DR_Z - X_S \tag{1}$$

Wherein; Y is the installation depth of the sensors, DR_Z is the depth of root development and X_S is the rate of re-advancement of the moisture front (Soil Moisture Redistribution) after the cut-off of irrigation, which is all in centimeters. The value of X_S varies in different soils and to determine it, it is necessary to perform a re-advances test of the moisture front in the soil profile.

3.1. Optimal device installation distance

Initially, the device was installed at 50% of the beginning of the furrow and flowed with a flow rate of 1.09 L/s. After turning on the warning light of the device, irrigation was stopped, and sampling was done from 10, 30, and 50 cm depths of soil at the beginning of the furrow, 50%, 75%, and 85% of the length of the furrow, and then at the end of the furrow, and its moisture was recorded. This was repeated for all the intervals mentioned. At the same time, the discharge of the furrows was considered the same. This will accomplish two things: first, according to the warning to cut off irrigation and record soil moisture, the reading of the device in the field can be verified, and the optimal depth of device installation can be obtained and generalized to other similar farms. Second, it determined the optimal length of device installation in furrow irrigation and calculated the parameters of efficiency, deep percolation losses, runoff, and irrigation adequacy.

Figure 4(F1) shows the soil moisture profile at three selected depths of 10, 30, and 50 cm. The drawn horizontal line (WR) shows the water requirement of the hypothetical maize plant in each irrigation interval, explaining that based on the 32% volumetric water requirement, judgments should be made based on moisture at a point of 50 cm because the plant root expansion and concentration system are located at that point. That is, if at a depth of 50 cm in the soil, the volume moisture content is 32%, it is desirable, and moisture more or less than this amount indicates water loss and deficit irrigation, respectively. As can be seen in **Figure 4(F1)**, at a soil moisture depth of 30 cm, the saturation limit at the beginning of the furrow has reached less than the water requirement at the end of the furrow. The main point is that if the device is installed at 50% of the furrow length and a depth of 30 cm from the furrow bed, after a period of cut-off irrigation, the moisture recorded at different soil depths indicates that more than 50% of the furrow length has been deficit irrigated and the remaining 50% has received more water than needed. Despite the small amount of deep percolation in the first 18 m of the furrow, due to the low adequacy of irrigation, it's not recommended to install the MRICAD device in the F1 furrow and cut off the irrigation after halfway. Due to the short duration of irrigation, the amount of runoff is low, and deficit irrigation has been applied at depths of 30 and 50 cm.

The amount of moisture after irrigation cut-off in different ratios of furrow length at 10, 30, and 50 cm soil depth for furrow F2 is shown in **Figure 4(F2)**. Due to longer irrigation times and naturally more water consumption than the F1 furrow (70 L), the amount of deficit irrigation at the end of the furrow has been reduced, and more excess water has been used for deep percolation at the beginning of the furrow, but the number of deep losses compared to furrows F3 and CF is less. Another point is the small amount of deficit irrigation done at the end of the furrow, which can be ignored. Therefore, according to the two points mentioned, the proportion of deficit irrigation rate and deep losses, as well as the amount of irrigation adequacy of more than 81%, in the in the F2 furrow means installing the device at 75% of the path length (from the beginning of the furrow) and a depth of 30 cm of soil is the best. Because in this case, water losses and deficit irrigation are minimal, and most importantly, the plant water requirement must be supplied within the depth of plant root development.

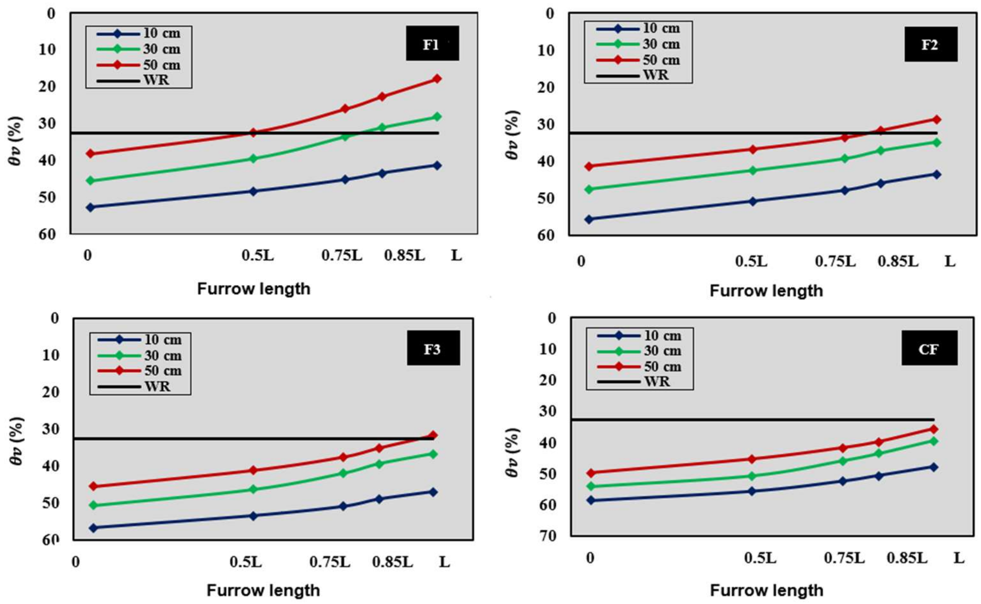

Figure 4. Recording of moisture in different furrow distances at a depth of 10, 30 and 50 cm of soil in furrows.

Figure 4(F3) shows the moisture distribution pattern of different ratios of furrow length at soil depths of 10, 30, and 50 cm in the F3 furrow after irrigation cut-off and soil sampling. Although irrigation adequacy is high (more than 93%), due to the high rate of deep percolation losses, this ratio of the length of the furrow is not suitable for installing the MRICAD device. In furrow F3, compared to furrows F2 and F1, 30 s and 90 s more water flowed in it, respectively, so the volume of water consumed is higher and the amount of runoff losses, especially deep percolation to the middle of the furrow, is significant. Because 85% of the length of the furrow is closer to the end of the field, excess water is lost from the end of the field as runoff, which is contrary to the objectives of this study. According to the above points, this status (furrow F3) does not have the necessary conditions to reduce losses at the beginning and end of the furrow, and the adequacy of irrigation isn't considered.

Figure 4(CF) shows the recording of moisture in different ratios of the furrow length at a depth of 10, 30, and 50 cm of soil in the CF furrow. It is well known that this furrow and the installation of the device at the end of the path are not suitable (even if the irrigation adequacy is 100%). Due to the longer irrigation time and the larger volume of irrigation water, the amount of deep percolation and runoff losses has its highest amount, and a large part of the given water is out of the plant's reach. This can be concluded even without testing, but the purpose of testing in this furrow was to investigate the optimal depth and length of the device installed in the same conditions for all furrows and to draw a pattern of moisture distribution in the soil profile for a fair judgment between them. Due to the longer duration of irrigation, the difference between water content at different depths is reduced, and in all three depths, the amount of moisture required is too much. Although the difference in the times of irrigation cut-off is small, due to the larger volume of water flowing, the amount of deep percolation and, generally, losses will also increase.

Table 2 shows the studied parameters in furrows, the most important of which are irrigation time, amount of water consumption, adequacy, and deep losses. It should be noted that the runoff was a leak and could not be measured by installing a flume. Before and after irrigation, the water content of the installation depth of the sensors, i.e., 30 cm, was recorded and then converted to a volume percentage. The device was installed at a depth of 30 cm, and the irrigation was stopped with a 65% moisture warning. After converting the measured moisture to actual volumetric moisture, the water content at this point was estimated to be about 40% by volume.

Table 2. Evaluation of adequacy, water volume, and irrigation time in the studied furrows.

Parameters	F1	F2	F3	CF
Water content before irrigation* (% θv)	17.5	17.5	17.5	17.5
Water content after irrigation* (% θv)	39.5	39.5	39.5	39.5
Irrigation time of furrow (s)	319	383	412	435
Discharge (L/s)	1.09	1.09	1.09	1.09
Volume of water consumption (L)	350	420	450	475
Deep percolation (% of irrigation volume)	36	84	95	100
Irrigation adequacy (%)	50	81	93	100

* Water content before and after irrigation was recorded by the device at a depth of sensor installation (30 cm).

In the first and second rows of **Table 2**, these parameters are shown. Another parameter is the irrigation time, which is the interval between the start of irrigation and the time when water reaches the sensor installed in each of the longitudinal ratios (different furrows), at which time the warning light announces the irrigation cut-off. The discharge of all furrows was considered to be the same. Other parameters, including volume of water consumption, deep percolation losses, and irrigation adequacy, are shown in **Table 2**.

3.2. Optimal device installation depth

In different soils and crops (due to the depth of root development), the depth of sensor application varies, and the moisture front moves at unequal speeds. Another purpose of the research is to find the optimal installation depth in the soil of the study field (loam) and generalize its relationship to other soils (light and heavy). The effective parameters in finding the optimal installation depth of the MRICAD device are the depth of root development and the movement of the moisture front from the end of the sensor to the end of the root after the time of irrigation cut-off. Because after the irrigation is stopped, the moisture front continues to move and reaches the lower layers, this advance is changeable depending on the conditions of the field, discharge, and soil. Since the F2 furrow was recognized as the best furrow in terms of water distribution, deep losses, and irrigation adequacy, the results of this furrow are used to investigate the optimal installation depth of the device. The results show that if the goal of irrigation is a water supply of 32 mm per irrigation interval and to bring the moisture front to a depth of 50 cm of soil, moisture sensors should be installed at a depth of 30 cm to achieve the best soil moisture distribution pattern (due to deficit irrigation, runoff, and deep percolation). According to Equation (1), there is no specific discussion about the depth of plant root development because it has a certain amount. The aim is to find the amount of X_S in soil, discharge, and different furrow sizes. Based on the results of this study, **Table 3** can be formed. Therefore, according to the flow rate of 1.09 L/s, root depth of 50 cm, loamy soil, and furrows of 36 × 0.75 m^2, the optimal installation depth can be achieved in light and heavy soils according to the conditions of this field. These results can be generalized to farms similar to those in this study.

Table 3. Optimal installation depth of the device in different soils according to the results of this research.

Kind of soil	X_S or the distance between the sensor to the end of the root depth (cm)	Y or installation depth of the device sensors taking into account the root depth of 50 cm
Light	28–34	50 – (28 – 34) = 16–22 cm
Medium	17–23	50 – (17 – 23) = 27–33 cm
Heavy	6–12	50 – (6 – 12) = 38–44 cm

4. Conclusion

Using smart irrigation methods to prevent deep percolation and runoff losses can be a good solution for crisis management and water conservation. The smart irrigation system has an essential role in optimal water consumption, and in different soil conditions, the type of irrigation system and the amount of water available are usable. Therefore, measuring the exact amount of volumetric water content is very important in agricultural sciences, hydrology, and soil science. For this purpose, a moisture sensor device was built to estimate soil moisture and prevent water losses, and for the first time, simultaneously with three sensors. Other objectives of this study were to find the optimal installation depth and different length ratios for the furrow irrigation method. The results showed that if the device is installed at a depth of 30 cm from the soil surface in the furrow and at a ratio of 75% from the beginning of the field, the deep percolation and runoff losses for this type of soil and discharge are minimal, and irrigation adequacy will be greater than at other depths (10 and 50 cm) and lengths (CF, F1, and F3). The observations of this research also proved that by using the constructed device, soil moisture can be directly monitored, and by using a smart irrigation system, the yield of crops and irrigation accuracy can be increased. Water losses will also be prevented, and more water will be saved.

Data availability statement

The data presented in this study are available in the article.

Author contributions

Conceptualization, MPA and AL; methodology, MPA; software, FN; validation, MPA and AL; formal analysis, MPA, AL and FN; investigation, MPA; resources, MPA and FN; data curation, MPA and AL; writing—original draft preparation, MPA; writing—review and editing, MPA, AL and FN; visualization, MPA and FN; supervision, AL; project administration, MPA; funding acquisition, AL and MPA. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the author.

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