Empirical modelling of wetting patterns in a controlled drip irrigation system for sandy loam soils

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Abstract. The soil wetting pattern is an important factor to fulfil the adequacy of water requirements in a controlled drip irrigation system. The soil wetting pattern is a parameter that is considered in the installation of irrigation systems and control instruments in the field. This study aimed to developed estimate vertical and horizontal soil wetting in the application of control systems using soil moisture sensor in drip irrigation systems. This research conducted in laboratory experiments with surface drip irrigation involved soil sample from pepper plantation, three discharge rates, and 26 soil moisture sensors. The empirical model provides estimated the soil wetted as a parameter of application time, emitter discharge, soil bulk density, initial soil moisture content, and saturated hydraulic conductivity. The development of empirical formulas for predicting wetted radius at different soil depths is carried out by non-linear regression analysis to obtain empirical best-fit coefficients. The empirical model of this study can estimate the full wetting pattern with acceptable accuracy and performs that represent a good performance of a controlled drip irrigation system. The result of performance appraisal validation for the wetted radius and wetted depth on sandy loam soils was assessed based on the lowest mean error was -2.86 and -0.284 cm as well as the highest efficiency model was 0.959 and 0.857 respectively.

1. Introduction

Bangka is one of the largest peppers producing regions in Indonesia, with total production estimated to reach 34,194 tons, equivalent to 39% of national production on an area of 51,583 ha [1]. Bangka was dry land, podzolic soil types were nutrient-poor and their physical condition was poor. On dry land, the use of groundwater for irrigation is less developed because the price is relatively expensive [2]. This condition is exacerbated by the characteristics of the porous soil (quartz-sand) and the high surface temperature of the soil, which causes the magnitude of the evapotranspiration value. Such a situation encourages the need for the use of water-saving irrigation technology [3].

One of the waters saving irrigation technologies is the drip irrigation system because wetting only occurs in the root zone of plants, thus minimizing the occurrence of percolation and evaporation [4]. This technology is very suitable to be applied in pepper plantations in Bangka, considering the shallow pepper root system [5] and the Bangka soil condition require accurate water supply. Drip irrigation which generally works based on scheduling the time has a weakness in operation, because the provision of water is often not in accordance with the actual water requirements of the plant. According to [6] this weakness can be overcome through the application of technology in the form of
soil moisture sensors that are used to measure the level of crop water requirements based on the availability of water in the soil.

In a controlled drip irrigation system, the soil moisture sensor is used as feedback to compare the results of measuring the actual soil moisture with the desired soil moisture (setting point). Feedback is used as the basis of on-off of the control actuator which consists of a water pump and solenoid valve, as the tools to distribute water from a water source to an emitter installed in the field through a drip irrigation installation system [7]. Obstacles encountered in the development of a controlled drip irrigation is constrained operating irrigation soil moisture in real time. According [8], error of the sensor reading is due to the inaccuracy of the sensor, reduced the operational capability of controlled drip irrigation in meeting plant water needs.

Based on these problems, it is necessary to use a sensor positioning simulation using a soil wetting pattern modeling approach. Modeling the soil wetting pattern will provide information about the depth and width of the spread and the amount of moisture content. The model of wetting pattern and moisture distribution in drip irrigation is influenced by various parameters consisting of the characteristics and properties of the system [9]. The development of an empirical model of the wetting and distribution pattern of irrigation water was used to estimate the dimensions of the wetting zone by including the effect of emitter discharge, application time, soil density, hydraulic conductivity and volumetric soil moisture content [10].

The modeling results are used for consideration of optimizing the positioning of moisture sensors. The right position of the sensor is expected to represent the actual condition of the plant root system in reading moisture content. The systems designed is expected to be able to overcome the problem of the accuracy of the operation of a controlled drip irrigation system, in the form of the ability to maintain water levels at available water levels from actual plant water requirements. Considered the condition of pepper plantation land in Bangka is podzolic and sandy soils with low water binding capacity/sensitive soil. Plant growth can be optimal with adequacy water supply despite of high evapotranspiration values, porous soil conditions and limited water availability.

2. Materials and Methods

2.1. Experimental Site

The materials used in the study were soil samples taken from pepper plantations in Bangka Regency, Bangka Belitung Islands. Soil samples were analyzed at the BPTP Yogyakarta Soil Laboratory. Research on wetting patterns was carried out in the Laboratory of Land and Water Resources Engineering, Department of Agricultural Engineering and Biosystems, Faculty of Agricultural Technology, Universitas Gadjah Mada.

2.2. Tools and Materials

The tools used in this study were 20 mesh sieves, sample rings, saucers, ovens and digital scales. The observation glass pattern of the wetting pattern is 40 cm long, 40 high and 10 cm wide. Drip irrigation installation with drip stick type emitters to deliver water from a 250liter capacity water tank. Soil moisture sensor as a measure of soil moisture content. Electronic control system as a soil moisture sensor controller and storage system for data retrieval in a in the data logger. Camera observation to see the wetting movements that occur visually. Stopwatch to manage time in research applications. The materials used were irrigation water and soil samples from pepper plantations in Bangka, Bangka Belitung Islands.

2.3. Research Procedure

This research was conducted in a series of stages, the procedure of this study is shown in Figure 1. The study began with literature studies followed by experimental design as set out in Figure 2, namely a set of soil moisture sensors with a control system in the observation glass plot. Placement of the soil moisture sensor in the observation glass plots which is filled with soil samples, according to the configuration in Figure 3. After the hardware functions properly, the study continues the application of
drip irrigation to the observation of glass boxes filled with soil samples and humidity sensors) as a whole system (Figure 1.).
2.4. Determination of irrigation volume

The wetting volume comes from the moisture content detected by the soil moisture sensor while the irrigation volume is obtained from the sum of the wetting volume of each contour (segment) in the wetting pattern in the available water range. The wetting volume is described as an ellipse so that the wetting volume considered to be equal to half of the ellipse volume with Equation 2.1:

\[ V = \frac{4}{3} \pi a d z \]  \hspace{1cm} (2.1)

\[ a = \text{wetting thickness (cm)} \]

\[ d = \text{wetting width (cm)} \]

\[ z = \text{wetting depth (cm)} \]
Determination of volumetric water content is derived from the wetting volume based on the moisture content detected by the soil moisture sensor. Given the soil moisture sensor used is capacitance based is the percent mass of water ($\theta_m$) from the gravimetric method. So, determine the volume of water ($\theta_v$) Equation 2.2 is needed:

$$\theta_v = \theta_m \frac{BD_{soil}}{BD_{water}}$$  \hspace{1cm} (2.2)

Where: $\theta_m$ =% mass of water; $\theta_v$ = volume of water, $BD_{soil}$= soil density and $BD_{water}$ = water density

2.5. Empirical model of wetting patterns

In the development of empirical models carried out by [10] from the formulas of the empirical model [11] This formula includes irrigation discharge, hydraulic conductivity, volumetric soil moisture content, irrigation time, and soil type. The new empirical model that has been developed consists of wetting width (Equation 2.3) and wetting depth (Equation 2.4), namely:

$$d = q a_1 k_s a_2 t a_3 \Delta \theta a_4 \rho_b a_5$$  \hspace{1cm} (2.3)

$$z = q b_1 k_s b_2 t b_3 \Delta \theta b_4 \rho_b b_5$$  \hspace{1cm} (2.4)

Where $z$ (cm) = vertical distance of wetting; $d$ (cm) = width of the wetting surface; $q$ (l/h) = emitter discharge; $ks$ (cm/h) hydraulic conductivity; $\Delta \theta$ ($L^3/L^3$) = average volumetric water content during irrigation; $\rho_b$ (g/cm$^3$) = period of soil type; and $t$ (h) = duration of irrigation. The values of $a1, a2, a3, a4, a5, b1, b2, b3, b4, b5$ are coefficients obtained from the coefficients obtained from the fitting model in non-linear regression analysis

2.6. Model performance evaluation

The model performance evaluation is based on a comparison of statistical parameters from simulated data (models) with observed data. The parameters used in the performance appraisal of the model are mean error ($ME$), root mean square error ($RMSE$), and efficiency model ($EF$). This parameter is calculated using the following formula [12]:

$$ME = \frac{1}{N} \left[ \sum_{i=1}^{N} (C_{si} - C_{oi}) \right]$$  \hspace{1cm} (2.5)

$$RMSE = \left[ \frac{1}{N} \sum_{i=1}^{N} (C_{si} - C_{oi})^2 \right]^{1/2}$$  \hspace{1cm} (2.6)

$$EF = 1 - \frac{\sum_{i=1}^{N} (C_{si} - C_{oi})^2}{\sum_{i=1}^{N} (C_{si} - Co)^2}$$  \hspace{1cm} (2.7)

where $N$ = total data; $C_{si}$ = simulation data; $C_{oi}$ = observation data; and $Co$ = average observation data. The values of $RMSE$, $ME$, and $EF$ are compared separately for the model of the width and depth of the moistened soil. The suitability of a good model is shown by a lower $RMSE$ value, a lower absolute value of $ME$, and an $EF$ value that approaches one [12].

3. Result and Discussion

3.1. Soil Physical Properties

The soil sample used in this study came from the Sungailiat area, Bangka Belitung Islands Province. The physical properties of the soil sample resulting from testing in the Laboratory are presented in Table 1.

| BV (g/cm$^3$) | BJ (g/cm$^3$) | Field capacity (%vol) | Wilting Point (%vol) | Porosity (%) | Hydraulic Conductivity (cm/hour) | Percentage of fractions |
|---------------|---------------|-----------------------|----------------------|--------------|---------------------------------|------------------------|
| 1,3           | 2,41          | 15,47                 | 8,58                 | 46           | 5,80                            | 21                     |
|               |               |                       |                      | 18           | 61                              |                        |
Based on the percentage of sand, silt and clay fraction test results, the soil texture used in this study is sandy loam soils. Soil samples are dominated by sand fractions which have relatively large particle diameters, so they have a small surface area [13]. Sands soil have more coarse pores than clay, seen from a large porosity value with a value of 46%. Land that contains a lot of rough pores is difficult to hold water so that the soil is easily drought [14].

The physical characteristics of the soil from the test results are in accordance with the type of soil in the Bangka region, which is podzolic soil, where the physical condition of the soil is poor mainly related to the binding capacity of the soil to water. This condition has resulted in poor land to be cultivated as plantation land [2].

3.2. Drip irrigation performance
The performance of drip irrigation is the result of determining the irrigation discharge value used in a controlled drip irrigation system. Arrangement of drip irrigation is carried out based on the openings of 3 types of faucet openings and head pressure with 3 replications which are appropriate by looking at the consistency of the water discharge produced. The best discharge results that will be used in a controlled drip irrigation system are presented in Table 2. It is an irrigation discharge with full tap openings and a height of 40-50 cm.

| Height / pressure (head) (cm) | Repetition 1 | Repetition 2 | Repetition 3 | Average discharge (cm³/min) |
|-----------------------------|-------------|-------------|-------------|--------------------------|
| 50                          | 27.33       | 26.67       | 27.00       | 27.00                    |
| 45                          | 26.33       | 26.00       | 25.67       | 26.00                    |
| 40                          | 25.67       | 25.67       | 25.33       | 25.56                    |
| 35                          | 25.67       | 25.33       | 25.67       | 25.56                    |
| 30                          | 24.67       | 24.67       | 24.67       | 24.67                    |
| 25                          | 24.00       | 24.00       | 24.00       | 24.00                    |
| 20                          | 23.33       | 23.33       | 23.33       | 23.33                    |
| 15                          | 22.67       | 22.67       | 22.67       | 22.67                    |
| 10                          | 21.67       | 21.67       | 21.67       | 21.67                    |
| 5                           | 21.67       | 21.67       | 21.67       | 21.67                    |

3.3. Volume of Drip Irrigation
The volume of drip irrigation is a combination of readings of the moisture content of the sensor by measuring the pattern of width and depth of wetting. Results from measurements of the depth and width of wetting that have been included in the half ellipsoidal volume equation (Equation 2.1) and volume of water (Equation 2.2).

Generally, overall replication in the application of drip irrigation showed good performance. The value of the volume of drip irrigation produced is good enough to show the performance of drip irrigation and reading by the soil moisture sensor as a control system. Likewise, a surge in the volume of drip irrigation is possible because of parallel reading of the moisture so that the performance of the sensor is weak.

The results of observations of wetting from the application of drip irrigation were used as an approach in determining the volume of irrigation. Changes in irrigation volume that occur have a pattern of change that is difficult to approach with a linear model. The volume surge also indicates that the wetting pattern model is non-linear. This condition is in accordance with the modelling method used in this study, namely the empirical model for non-linear.
3.4. Empirical model of wetting patterns

Based on the results of the tests that have been done, the values of each parameter are obtained in Equation 2.3 and Equation 2.4. At the q value as the drip irrigation application discharge, the value is 1.534 l/hour. The value of $Ks$ as the hydraulic conductivity of the soil sample has a value of 5.796 cm/hour. The value of $t$ or irrigation application time used is 90 minutes with data retrieval intervals of 6 minutes. $\Delta \theta$ is the average volumetric soil water content during irrigation at each time interval from equation 2.2. The value of $\rho$ (Table 4.1) is 2.41 g / cm$^3$. While the values of $a1$, $a2$, $a3$, $a4$, $a5$ and $b1$, $b2$, $b3$, $b4$, $b5$ are empirical coefficients obtained from the fitting model in non-linear regression analysis.

Based on the analysis of the observations and non-linear regression fitting models, the coefficient values used in Equations 2.3 and 2.4 are obtained. The model is evaluated for the performance of the model, based on a comparison of statistical parameters from the data model with observational data on each replication. The parameters used are mean error (ME), root mean square error (RMSE), and efficiency model (EF).

Table 3. Empirical validation coefficient of wide wetting model

| Coefficient | Value     |
|-------------|-----------|
| $a1$        | 1.334096  |
| $a2$        | 0.651454  |
| $a3$        | 0.144475  |
| $a4$        | 0.208407  |
| $a5$        | 0.964919  |

$$d = q^{1.334} Ks^{0.651} \Delta \theta^{0.208} \rho^{0.965}$$

Tabel 4. Evaluation of the performance of a wide model of wetting validation

| Parameter | Value     |
|-----------|-----------|
| SSD       | 7.789136  |
| ME        | -0.28462  |
| RMSE      | 0.720608  |
| EF        | 0.959458  |

The validation stage of the wide wetting model begins with verification of the model against the two replications to get the parameter coefficient value. Based on the verification of the wide wetting model that has been done, the parameter coefficient values of the fitting model will be used in the validation stage shown in Table 3. The results of the model verification performance provide low SSD, ME and RMSE values and EF or $R^2$ values which are 0.959 which are close to 1. that the parameter coefficient of verification of the model is good for use in modelling the width of wetting.

The validation results along with the performance of the width wetting model are shown in Table 4. The results of the validation show the performance of a good model with a minimum value on the SSD of 7.789, ME of -0.285 and RMSE of 0.721. This condition shows the low deviation that occurs between the width of the prediction wetting (model) on the width of wetting observation (observation). Also supported by the value of EF or $R^2$ which is close to 1, which is 0.959, shows a strong determinant coefficient. Parameters of model performance assessment indicate that the equation is a good model to predict the width of wetting in a controlled drip irrigation system.

Table 5. Empirical validation coefficient of depth wetting model

| Coefficient | Value     |
|-------------|-----------|
| $b1$        | 1.17628   |
| $b2$        | 0.678073  |
| $b3$        | 0.164153  |
| $b4$        | 0.51936   |
| $b5$        | 1.058003  |
The validation stage of the wetting depth model begins with verification of the model on both replications to obtain the parameter coefficient value. Based on the verification of the depth wetting model that has been done, the parameter coefficient values of the fitting model will be used in the validation stage shown in Table 6. The results of the model verification performance provide low SSD, ME and RMSE values and EF or $R^2$ values of 0.858 which are close to 1. Value This shows that the parameter coefficient of verification of the model is good for use in modelling in determining the depth of wetting.

The results of the validation along with the performance of the wide wetting model are shown in Table 6. The results of the model performance provide SSD values of 144.3, ME of -2.861 and RMSE 3.104 shows a tend to small value. This condition shows a deviation between the depth of the prediction wetting (model) to the depth of wetting observation (observation), even though it is of little value. Supported by EF value or $R^2$ which is still close to 1, which is 0.857, shows a tend to strong correlation. That this equation can still be a good model to be able to predict the depth of wetting in a controlled drip irrigation system.

Table 6. Evaluation of the performance of a depth model of wetting validation

|     |     |
|-----|-----|
| SSD | 144.2999 |
| ME  | -2.8606  |
| RMSE| 3.104375 |
| EF  | 0.857183 |

The validation stage of the wetting depth model begins with verification of the model on both replications to obtain the parameter coefficient value. Based on the verification of the depth wetting model that has been done, the parameter coefficient values of the fitting model will be used in the validation stage shown in Table 6. The results of the model verification performance provide low SSD, ME and RMSE values and EF or $R^2$ values of 0.858 which are close to 1. Value This shows that the parameter coefficient of verification of the model is good for use in modelling in determining the depth of wetting.

The validation stage of the wetting depth model begins with verification of the model on both replications to obtain the parameter coefficient value. Based on the verification of the depth wetting model that has been done, the parameter coefficient values of the fitting model will be used in the validation stage shown in Table 6. The results of the model verification performance provide low SSD, ME and RMSE values and EF or $R^2$ values of 0.858 which are close to 1. Value This shows that the parameter coefficient of verification of the model is good for use in modelling in determining the depth of wetting.

4. Conclusion

Modelling of wetting patterns and distribution of water in controlled drip irrigation was carried out using empirical model applications. The parameters used in the empirical model are $q$ (L/h) = irrigation discharge rate; $K_s$ (cm/h) = hydraulic conductivity; $\Delta \theta$ (L/L$^3$) = average volumetric groundwater content, $t$ (h) = irrigation time, and $\rho_b$ (g/cm$^3$) = soil bulk density In modeling the width of the wetting pattern (d) we use the equation $d = q^{1.334} K_s^{0.651} t^{0.145} \Delta \theta^{0.028} \rho_b^{0.965}$ while the wetting depth (z) uses the equation $z = q^{1.176} K_s^{0.678} t^{0.164} \Delta \theta^{0.519} \rho_b^{1.058}$. The results of the validation of d equations are SSD = 7.789, ME = -0.285, RMSE = 0.721 and $EF$ or $R^2$ values which are close to 1, which is 0.959. Whereas z equation is SSD = 144.3, ME = -2.861, RMSE = 3,104 and $EF$ value or $R^2$ which is close to 1, which is 0.857. This value shows the low deviations that occur in the width and depth of the wetting of predictions (models) on the width and depth of wetting observation (observation) by showed a strong correlation coefficient.

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