Fattahi Nafchi *et al.*
Journal of Engineering and Applied Science (2023) 70:126
https://doi.org/10.1186/s44147-023-00295-5

Journal of Engineering and Applied Science

REVIEWS

Open Access

Evaluation of wetting front detector to estimate the dimensions of wetting front in the drip irrigation

Rouhallah Fattahi Nafchi[1], Milad Valiyari-Eskandari[1], Hamid Raeisi Vanani[1], Kaveh Ostad-Ali-Askari[2,3*] and Abbas Bahrami[1]

*Correspondence: ostadaliaskari.k@of.iut.ac.ir

[1] Water Engineering Department, College of Agriculture, Shahrekord University, Shahrekord 88186-34141, Iran
[2] Department of Civil Engineering, School of Engineering, American University in Dubai, Dubai, 28282, United Arab Emirates
[3] Department of Irrigation, College of Agriculture, Isfahan University of Technology, Isfahan 8415683111, Iran

Abstract

In order to achieve proper water consumption efficiency in micro-irrigation systems, the space and flow rate of the drippers should match the hydraulic characteristics of the soil and the time and amount of plant irrigation water. As a result, having proper information about the width and depth of the wetted soil (wetting volume) is essential for the design, planning, and proper management of drip irrigation systems. The aim of this study was to obtain a set of semi-empirical relationships for more accurate and easier estimation of the diameter and depth of the wetting front. Field data of drip irrigation systems were collected by wet front detector (WFD) installed in three different conditions in terms of soil texture and flow rates of 4 and 8 L/h. Due to the technical problems and errors in the measurement of saturated hydraulic conductivity, which is the main representative of soil properties, the relationships presented here estimate the dimensions of the wetted soil volume based on the infiltration time and the volume of water stored in the reservoir. No need for hydraulic conductivity of the soil. The equations obtained in this research predict the diameter and depth of the wetted soil volume with a correlation coefficient of 89 and 98%, respectively.

Keywords: Drip irrigation, Wetting front detector (WFD), Advance front, Hydraulic conductivity

Introduction

Design of drip irrigation system must be done based on the position of the wetting soil pattern under emission points and the instantaneous position of the wetting front depends not only on the hydraulic characteristics of the emitters but also on the physical properties of the soil such as texture, structure and hydraulic conductivity [15, 2, 4, 7, 19, 20]. Dimensions of the wetting front are function of irrigation time, water volume, and soil type and it is necessary for determining optimum design parameters. Moisture distribution pattern in different soil is important for the following reasons: (a) Accurate design of irrigation system components,b) Improving irrigation efficiency and systems operation with an accurate distribution of water and fertilizer in root depth; (c) optimization irrigation planning; (d) matching the time and location of wetting dimensions with steps of plant root growth. Based on the soil wetting pattern, the length, width, and depth of the moisture front can be determined. Actually, in sandy soils emitters were considered more near because due to the vertical velocity of water and narrow dimensions of wetted volume while in clay soils further emitters are needed because of horizontal movement of water and wide wetted volume [12, 21]. Irrigation time depends on the traveling time of the wetting front to the depth of the roots or a fraction of it. Distance between emission points (S_e), emission rate (q_e), and irrigation time (T_i) should be determined in a way that wetted soil volume is shaped according to the plant's root. Therefore, studying wetting soil patterns and volume beneath emission points is necessary for providing the plant water needs, optimal managing of the water and nutrients, and in particular increasing irrigation efficiency. Peter et al. [14] have concluded by examining the vertical and horizontal dimensions of the wetted soil by porous pipes in two groups of soils that in the first group of soils, with less preserved structure, increasing the amount of clay particles, the shape of wetted soil is spherical and the diameter of spherical section increases downward the pipe position. In the second soil group, the dimensions of the wetting soil are independent of its texture and the wetted Section is amorphous. Therefore, soil texture is unreliable for predicting the wetting dimensions. Rahimzadegan [16] based on the movement of water in the soil, concluded that when the water starts to flow, the wetting pattern with lower flow deeper and with higher flow moves horizontally. The effect of emitter yield on moisture patterns and moisture distribution in sandy soils was investigated by Thabet and Zayani [25] that the vertical advance of water in emitters with lower yield is higher than those with higher yield. As the moisture radius increases, the yield increases, but after 180 min from the start of the experiment, the highest wetting radius was due to lower yield. Researchers have performed different experiments to compare soil moisture content from a linear source in soils with different textures. They have studied the effect of different flow rates on the moisture distribution of soil under drip irrigation in fruit and citrus orchards and crops. They also concluded that the lateral movement of water in clay-textured soils is higher than in coarse-textured soils [3, 9, 13]. Determining and monitoring the moisture front in the root development area was very time-consuming and expensive. Therefore, many researchers have tried to predict the progress of the wetting front by presenting various physical and numerical equations and models. Accordingly, simulation models can be a suitable replacement for issues related to the movement and distribution of water [22–24]. Using mathematical equations, Roth [17] obtained a relationship to determine the radius of wetting with the help of the soil moisture parameters caused by the dripper and the duration of irrigation.

Wetting front detector is a new, simple, and efficient device and is designed for accurate and adequate irrigation and helps farmers to better manage water and fertilizer. The depth of water penetration in the soil and the pattern of moisture distribution in the soil are determined by this device. Therefore, by correcting the irrigation time and irrigation flow rate (accurate determination of the amount of water required), the loss of irrigation and fertilizer, which includes deep infiltration and runoff, can be avoided [5, 6, 22]. Philip [15] with the analytical solution of Richards equation, has presented relationships for estimating the dimensions of the wetting front. However, some constraints such as homogeneity and heterogeneity of soil environment, irregular geometric shape of the flow path, and nonlinearity relevant equations, caused excessive simplifications of phenomena. By combining empirical field measurements and some soil hydraulic properties in numerical and analytical models, quasi-empirical models can be derived through mathematical modeling and the application of nonlinear multivariate regression, dimensional analysis, or neural network. Abbas Pelangi and Akhund Ali [1] in the sand dunes area of Albaji region of Khuzestan investigated the parameters of the development of wetting dimensions and also evaluated the results of Schwartzman and Zor (1986) models. The results of their research indicate the inadequacy of the model in estimating sandy dimensions of wetting in the Al-Baji Region. The similarity of the conditions of some soils and the climatic suitability can never guarantee the appropriateness of the extracted relationships in other areas. Therefore, this issue indicates the need to achieve special relationships for the soils of each region with the conditions of its drip irrigation method. Using the volume of wet soil and Buckingham's π theorem and dimensional analysis, quasi-empirical relationships were presented by Mirzaei et al. [11] and the values of the correlation coefficient (0.989 and 0.992) for the wet diameter and depth were in good agreement with the measured data. In addition, the proposed equation is a function of time, so that at any time it is possible to calculate wet diameter and depth. Using Buckingham's π theorem and considering the amount of hydraulic conductivity of soil saturation, emitter flow rate, and irrigation time, the maximum depth, and diameter of wet soil were calculated by Khan-Mohammadi and Besharat [8]. The high correlation coefficient value and the low average absolute error in estimating the depth and diameter of the wet soil show that the determination of the geometric dimensions of the wet front has been calculated with high precision with the help of quasi-empirical equations. In order to achieve quasi-empirical equations for determining the depth and diameter of wetting front in drip irrigation using simple wet soil detector tools, this research was carried out in the natural conditions of drip irrigation operations, in soils with different textures and water application flow rates.

The use of modern irrigation systems is one of the solutions to fight against the water crisis, especially in areas with hot and dry climates like Iran. Drip irrigation is one of these new systems of high rainfall many factors are involved to make it more efficient, such as design and implementation, maintenance, and proper operation. In the design discussion, it is very important to consider all the parameters of the soil, water, dripper, etc., in order to design more accurately and as a result to achieve an efficient system. Observing and predicting the perimeter that the dripper wets in order to deliver water to the root perimeter can be very important. As a result, providing mathematical formulas and relationships and providing models in this field can make the design and implementation of drip irrigation systems more efficient. Therefore, this research has addressed this issue and presented this model and relationships.

Materials and methods

In this study, wetting front detector (WFD) was used in the drip irrigation to determine the dimensions of the Wetting Front in three regions with different soil textures such as coarse, medium, and heavy soils under two different flow rates. To conduct this research, the first area was the farm of the Agriculture College, of Shahrekord University; the second was the greenhouse of Isfahan Municipality and the third was selected

Table 1 Some physical characteristics of soils in the three studied regions

Region	Soil depth(cm)	Bulk density (gr/cm^3)	Equivalent Saturation hydraulic conductivity (m/day)	Clay (%)	Silt (%)	Sand (%)	Texture
Shahrekord	0–90	1.41	3.6	35	65	15	Sandy clay loam
Isfahan	0–90	1.39	0.87	35	65	40	Clay loam
Fereidan	0–90	1.46	4.14	15	85	65	Sandy loam

in the agricultural lands of Fereidan city. In this study, the flow rates of the emitters were considered in 4 to 8 L/h range from three types of soil texture and at three different regions. The saturated hydraulic conductivity of the soils was obtained by the inverse well method. Soil texture was determined by sampling from the fields and using the hydrometric method in the laboratory and from the soil texture triangle. The soil texture characteristics of the three regions are presented in Table 1.

In three regions, water was transferred to the test site through a tube with a diameter of 32 mm and then was branched by a 16-mm lateral tube. The pressure was controlled by a barometer during the test. The drippers were used for flow rates of 4 and 8 L/h with the Euro drip type and were calibrated for these nominal flow rates. In the root area of each tree, five WFD devices placed (wetting front detector) radially and at three depths of 30, 50, and 80 cm for following the infiltrated water into the soil and determining the amount of deep flow rate.

As shown in the figure, two devices were installed at depths of 30 and 50 cm. In order to detect of wetting front, special sensors were made and then installed at the down of the water reservoir device. These sensors are sensitive to wet. When the water reaches a special depth, time is recorded by sensors. In order to stabilize the damaged soil, after installing of WFD device in the position, three times were irrigated and then the main experiments were performed to measure the parameters under study. The experiment was performed in each area and three positions and three replications. Obtained results from the measurements were used to derive empirical equations to determine the dimensions of the wetting front and to estimate the transverse and depth progress of the wetting front.

Empirical equation for soil moisture wetting front

To achieve a practical equation for predicting the instantaneous dimensions of a wetting front, WFD data such as the volume of stored water in the reservoir and the time that water reaches the considered depth were used as the most important independent variables for determining the wetting front through the application of nonlinear multivariate regression. For evaluating the equation, the results were compared with the obtained empirical equations by other researchers such as Schwartzman and Zur [18] and Naglic et al. [12] using the P-Buckingham theorem. While the soil hydraulic conductivity is a three-dimensional vector quantity, the shape and dimensions of the moisture below a point power supply depended on the ability to conduct water in three directions *X*, *Y*, and *Z*. On the other hand, determining the hydraulic conductivity in natural soil and three directions is very difficult and it faces many uncertainties. Even the determination of this property in one direction is usually done in disturbed samples, which are different than natural soil conditions. Therefore, with the aim of developing and creating simple equations for accurate prediction and field measurements, the saturated hydraulic conductivity was removed and the time of water reaching to device sensor and the volume of accumulated water in the reservoir were considered as parameters affecting the progress of the wetting front in the soils. Accordingly, the following functions were defined to determine the diameter and depth of wetting in the SPSS version 24 software as follows Eqs. 1 and 2:

$$D_W = a_1 \times V^{b_1} \times t^{c_1} \tag{1}$$

$$Z = a_2 \times \left(\frac{t}{t_{50}}\right)^{b_2} \times \left(\frac{V}{V_{50}}\right)^{c_2} \tag{2}$$

In these equations, DW is the wetting diameter and Z is wetting depth, and V and t are introduced as the volume of accumulated water and the reaching time of the front to the detector at a certain depth, respectively. V50 and t50 are the volume of accumulated water and the reaching time of the front detector at a depth of 50 cm, respectively, and a_1, b_1, c_1, a_2, b_2, and c_2 are the empirical coefficients of the equations. For obtaining appropriate relationships by using the empirical equations for investigating the dimensions of the wetting front and statistical analysis, SPSS version 24 and Excel2014 statistical software were used. Coefficient of determination (R^2) was used to evaluate the results. Comparison of the results of the equation with the obtained data from field experiments and evaluation of the accuracy degree of the equation was performed by t test 2 with a probability level of 95% and a significant level of 5%.

Results and discussion

The process of developing of wetting front was carried out by placing moisture detection sensors at the bottom of the water reservoir device and recording the wetting front time. The main purpose of using mathematical models in predicting soil–water relations is faster and less costly measuring. In fact, models are considered the best tools for empirical and laboratory research, because the results are obtained faster with less time and cost.

Equations for determining the position of wetting front

Hydraulic conductivity as a characteristic component of soil is one of the required parameters of the Schwartzman equation and other researchers. Due to the high difficulty and error of measuring this parameter, the probability of making an error in the results of the equation is increased. For this purpose, in this study, by placing the WFD device in the soil and using the obtained data from it on the farm, a quasi-empirical equation was introduced without the need to calculate hydraulic conductivity. The values of a, b, and c for wetting diameters (in Eqs. 1 and 2) were obtained 69.206, 0.272, and − 0.268, and for wetting, depths were 49.83, 0.522, and − 0.014, respectively and the following equations were obtained using multivariate nonlinear regression to estimate the instantaneous diameter and wetting depth as follows Eqs. 3 and 4:

$$Dw = 69.205 \times t^{0.272} \times {V_{WFD}}^{-0.268} \tag{3}$$

$$Z = 49.83 \times (\frac{t}{t_{50}})^{0.52} \times (\frac{V_{WFD}}{V_{WFD_{50}}})^{-0.14} \tag{4}$$

Note that in these equations t is equal to V/q, so the relationship of wetting pattern and flow rate is also considered. Values of the measured diameter in the farm and the estimated diameter from the quasi-empirical equation using t test and F tests are presented in Table 2.

According to the values in the table, the significance level (p value) of the Loon test for all three depths of 30, 50, and 80 cm is more than 0.05. This means that the variance of the measured and calculated values are as same and the value of the significance level is greater than 0.05. It can be said that there is no difference between the measured wetting diameter in the farm and the values estimated by the equation. In Table 3, the field data and the obtained data from the empirical equation related to the penetration depth are compared by t test which has equal variance, and considering the level of significance greater than 0.05, there is no significant difference between the measured values and the estimated values by the empirical equation for the wetting depth.

As in all models and obtained equations in this study be observed, irrigation time and consequently the volume of applied water is the most affected by the expansion of the wetting front because its exponential value in these equations is greater. Time exponential of reaching water to relevant depth for the wetting diameter and depth obtained were 0.27 and 0.52, respectively, which is close to the values of Naglic et al. [12] and Malek and Peter [10] equations, which indicate the high adequacy of the model for predicting the requested parameters. Also, the wetting depth equation relative to the wetting diameter equation shows that the deep infiltration of water is greater than its horizontal expansion, which corresponds with the results of Liu et al. Using Eqs. 3 and 4, it is possible to estimate Dw and Z, using the volume of accumulated water (m3/h) in the installed water reservoir device at the specified depth and the time of reaching of water (min) to

Table 2 Comparison of measured diameter with calculated values

Significance level	*t*	Significance level (Leven's test)	*F*	Depth (cm)
0.81	0.24	0.44	0.614	30
0.81	0.24	0.47	0.52	50
0.54	0.63	0.30	1.127	80

Table 3 Comparison of measured depth with calculated values

Significance level	*t*	Significance level (Leven's test)	*F*
0.99	− 0.009	0.913	0.012

the water reservoir of WFD device. Suitable agreement of the field experiments results with obtained equations in this study were showed so that the correlation coefficient of the measured and estimated values for the wetting diameter and the depth of water infiltration in the soil were 89 and 98%, respectively, which been shows the accuracy and precision of estimating the dimensions of wetting front by these equations. There is a slight difference between the correlation coefficients of diameter and measured depth estimated in this study, compared to the obtained coefficients by Mirzaei et al. [11] and Khan Mohammadi and Besharat. The reason for the difference in the value of the correlation coefficient is the obtained equations from the empirical results or numerical simulations which in comparison with the results of field experiments, more regular patterns and more accurate answers will be obtained, while the results of field experiments are more practical.

These are empirical equations that relate the parameter in question to the factors that affect it. Then, based on experimental results and field measurements, the amount of diameter and depth soaked two or more times and the volume of water consumed from the water supply source is measured and these parameters are obtained by software or even by the two-point method of these two equations and the validity of these equations was checked by regression, R^2, and t test method to determine the real parameters. After determining the parameters and variables of the equations of the wetted diameter and the measured and calculated depth, they were compared and the validity of these equations was based on the regression method (R^2) and t test method was checked. The units of the parameters are metric and the depth and width of wetting are in meters, time is in seconds and volume is in cubic meters.

Conclusions

The purpose of this study was to determine the quasi-empirical equations for easier and more accurate estimating of the dimensions of the wetting front in drip irrigation. The results of this study showed that by using a simple WFD device and installing it in natural soil conditions around the plant roots, the position and dimensions of the wetting front in the drip irrigation can be accurately traced and measured. The advantage of the WFD device in this test is the lack of need to determine the soil saturation permeability coefficient. The use of saturation hydraulic conductivity in the depth direction, in addition to considering one-dimensional flow, homogeneity of soil, and measurement errors due to the use of disturbed samples are the reason for the error in determining this important parameter for the optimal management of water and fertilizer in drip irrigation. The dimensions of the wetting front are determined for the proper design and planning of the drip irrigation system by using the obtained equations by directly measuring the pattern of progress of the wetting front in the soil. On the other hand, irrigation time can be determined according to special soil and the need to a certain volume of wetting of soil for each plant.

Acknowledgements

Not applicable.

Authors' contributions

RFN, MVE, HRV, KOAA, and AB designed the study, collected data, wrote the manuscript, and revised it. All authors have read and approved the manuscript.

Funding
Funding information is not applicable. No funding was received. No grants were received.

Availability of data and materials
Some or all data, models, or codes generated or used during the study are available from the corresponding author by request.

Declarations

Ethics approval and consent to participate
The present study and ethical aspect was approved by the Water Engineering Department, College of Agriculture, Shahrekord University, Shahrekord, 88186–34141, Iran. RFN, MVE, HRV, KOAA, and AB designed the study, collected data, wrote the manuscript, and revised it. All authors have read and approved the manuscript.

Consent for publication
RFN, MVE, HRV, KOAA, and AB agree to publish this manuscript. There is no conflict of interest. All authors have read and approved the manuscript.

Competing interests
The authors declare that they have no competing interests.

Received: 20 June 2023 Accepted: 2 October 2023
Published online: 13 October 2023

References

1. Abbas Palangi J, Akhond Ali AM (2008) A semi-empirical model for estimating the geometry of the wetting front under point source trickle irrigation. J Sci Technol Agric Nature Resour 12(44):85–96
2. Al-Ogaidi AAM, A Wayayok, MK Rowshon, AF Abdullah. 2016. Wetting patterns estimation under drip irrigation systems using an enhanced empirical model. Agricultural Water Management Volume 176 Pages 203–213 ISSN 0378–3774. https://doi.org/10.1016/j.agwat.2016.06.002
3. Appels WM, R Karimi. 2021. Analysis of soil wetting patterns in subsurface drip irrigation systems – Indoor alfalfa experiments. Agricultural Water Management Volume 250 106832 ISSN 0378–3774. https://doi.org/10.1016/j.agwat.2021.106832
4. Ayars JE, Fulton A, Taylor B (2015) Subsurface drip irrigation in California-here to stay? Agriculture Water Management. pp 39–47 (In Press)
5. Biswas TK, Schrale G, Stirzaker R (2008) New tools and methodologies for in situ monitoring of root zone salinity and leaching efficiency under drip and sprinkler irrigation. Acta Hort 79:115–122
6. Ibragimov N, M Avliyakulov, N Durdiev, SR Evett, F Gopporov, N Yakhyoeva. 2021. Cotton irrigation scheduling improvements using wetting front detectors in Uzbekistan. Agricultural Water Management Volume 244 106538 ISSN 0378–3774. https://doi.org/10.1016/j.agwat.2020.106538
7. Karimi B, P Mohammadi, H Sanikhani, SQ Salih, ZM Yaseen. 2020. Modeling wetted areas of moisture bulb for drip irrigation systems: an enhanced empirical model and artificial neural network. Computers and Electronics in Agriculture Volume 178 105767 ISSN 0168–1699. https://doi.org/10.1016/j.compag.2020.105767
8. Khanmohamadi N, Besharat S (2013) Simulating wetting front in drip irrigation using HYDRUS-2D. Journal of Water and Soil Resources Conservation 2(4):15–27
9. Koo RCJ, Tucker DPH (1975) Soil moisture distribution in citrus groves under drip irrigation. Citrus Industry 56:12–17
10. Malek K, Peters RT (2011) Wetting pattern models for drip irrigation: new empirical model. Irrigation and Drainage Engineering 37:230–237
11. Mirzaei F, Liaghat AM, Sohrabi TM, Omid M (2005) Simulation of the wetting front from a linear source in tape irrigation systems. Journal of Agricultural Engineering Researchs 6(23):53–66
12. Naglic B, Kechavarzi C, Coulon F, Pintar M (2014) Numerical investigation of the influence of texture, surface drip emitter discharge rate and initial soil moisture condition on wetting pattern size. Irrigation Sci 6:421–436
13. Nazari E, S Besharat, K Zeinalzadeh, A Mohammadi. 2021. Measurement and simulation of the water flow and root uptake in soil under subsurface drip irrigation of apple tree. Agricultural Water Management Volume 255 106972 ISSN 0378–3774 https://doi.org/10.1016/j.agwat.2021.106972
14. Peter J, Thorburn J, Cook F, Bristow LK (2003) Soil-dependent wetting from trickle emitters: implications for system design and management. Irrigation Sci 22:121–127
15. Philip JR (1984) Travel time for buried and surface infiltration point source. Water Res 60(7):77–74
16. Rahimzadegan R (1977) Water movement in field soil from a point source. Master of Science thesis, Utah State University, Logan, Utah, USA, pp 78–83
17. Roth RL (1974) Soil moisture distribution and wetting pattern from a point source. Proceedings of 6nd international drip irrigation congress, California (642–620)
18. Schwartzman M, Zur B (1986) Emitter spacing and geometry of wetted soil volume. Irrigation drainage Engineering ASCE 112:242–253
19. Shiri J , B Karimi, N Karimi, MH Kazemi, S Karimi. 2020. Simulating wetting front dimensions of drip irrigation systems: Multi criteria assessment of soft computing models. Journal of Hydrology Volume 585 124792 ISSN 0022–1694. https://doi.org/10.1016/j.jhydrol.2020.124792

20. Skaggs TH, Trout TJ, Rothfuss Y (2010) Drip irrigation water distribution patterns: effects of emitter rate, pulsing, and antecedent water. Soil Sci 74:112–132
21. Solat S, F Alinazari, E Maroufpoor, J Shiri, B Karimi. 2021. Modeling moisture bulb distribution on sloping lands: Numerical and regression-based approaches. Journal of Hydrology Volume 601 126835 ISSN 0022–1694. https://doi.org/10.1016/j.jhydrol.2021.126835
22. Stirzaker RJ, Hutchinson PA (2005) Irrigation controlled by a Wetting Front Detector: field evaluation under sprinkler irrigation. Australia Soil Research 43:935–943
23. Stirzaker RJ, TC Maeko, JG Annandale, JM Steyn, GT Adhanom, T Mpuisang. 2017. Scheduling irrigation from wetting front depth. Agricultural Water Management Volume 179 Pages 306–313 ISSN 0378–3774. https://doi.org/10.1016/j.agwat.2016.06.024
24. Subbaiah R (2011) A review of models for predicting soil water dynamics during trickle irrigation. Irrigation Sci 30(3):662–621
25. Thabet M, Zayani Kh (2008) Wetting patterns under trickle source in a loamy sand soil of south Tunisia. Agriculture Environment Sci 3:38–42

Publisher's Note