How to cite: Demir, V., M. Kilic, H. Yürdem, M. Neugebauer & R.C. Akdeniz, 2025. A simulation model for estimating 2D wetting patterns in drip irrigation systems. Ege Univ. Ziraat Fak. Derg., 62 (4): 465-476, https://doi.org/10.20289/zfdergi.1527322

Research Article
(Araştırma Makalesi)

Ege Üniv. Ziraat Fak. Derg., 2025, 62 (4):465-476
https://doi.org/10.20289/zfdergi.1527322

A simulation model for estimating 2D wetting patterns in drip irrigation systems

Damla sulama sistemlerinde 2B ıslatma desenlerinin tahmini için bir simulasyon modeli

Vedat DEMİR[1]

Murat KILIC[2 *]

Hüseyin YÜRDEM[1]

Maciej NEUGEBAUER[3]

R. Cengiz AKDENİZ[1]

[1]Ege University, Faculty of Agriculture, Department of Agricultural Engineering and Technologies, 35100, Bornova, İzmir, Türkiye

[2]Ege University, Faculty of Agriculture, Department of Agricultural Structures and Irrigation, 35100, Bornova, İzmir, Türkiye

[3]Warmia and Mazury University, Faculty of Technical Sciences, Department of Electrotechnics Energetics Electronics and Automatic, Olsztyn, Poland

* Corresponding author (Sorumlu yazar):

kilic.murat@ege.edu.tr

Received (Alınış): **10.10.2025** **Accepted** (Kabul Tarihi):**17.07.2025**

Keywords: Emitter, mathematical modelling, pressurized irrigation, trickle irrigation, water movement

Anahtar sözcükler: Damlatıcı, matematiksel modelleme, basınçlı sulama, damla sulama, su hareketi

ABSTRACT

Objective: The aim of this study is to develop a model that allows the 2D wetting pattern that occurs in drip irrigation systems to be analytically defined.

Material and Methods: In the model, the wetting pattern is simulated as a truncated ellipse. Wetting radius at the soil surface, the maximum wetting depth and width in the soil profile, and the depth of this maximum wetting width from the soil surface were taken into account. The experiments were carried out under uniform profile conditions and on soil samples with a loamy sand texture. The investigation was carried out for different emitter discharges.

Results: The wetting radius, maximum wetting depth, and cross-sectional area of the wetting pattern occurring at any time t of the water application period under each emitter discharge are estimated with the determination coefficients of 0.961, 0.947 and 0.995, respectively, by the numerical models developed in this study. The results show that the values of 2D cross-sectional area also increase as the emitter discharge increases.

Conclusion: The results of this study indicate that the proposed model defines the overall shape of the wetting pattern and can be used to determine the cross-sectional area of the pattern.

ÖZ

Amaç: Bu çalışmanın amacı, damla sulama sistemlerinde oluşan 2 boyutlu ıslatma deseninin analitik olarak tanımlanmasına olanak tanıyan bir model geliştirmektir.

Materyal ve Yöntem: Modelde ıslatma deseni kesik elips olarak simüle edilmiştir. Toprak yüzeyindeki ıslatma yarıçapı, toprak profilindeki maksimum ıslatma derinliği ve genişliği ve bu maksimum ıslatma genişliğinin toprak yüzeyinden itibaren derinliği dikkate alınmıştır. Denemeler, uniform toprak profili koşullarında ve tınlı kum bünyeye sahip toprakta gerçekleştirilmiştir. Araştırma, farklı damlatıcı debilerinde gerçekleştirilmiştir.

Araştırma Bulguları: Bu çalışmada geliştirilen sayısal modeller, farklı damlatıcı debilerinde herhangi bir t anında oluşan ıslatma yarıçapı, maksimum ıslatma derinliği ve ıslak kesit alanını sırasıyla 0.961, 0.947 ve 0.995 belirleme katsayıları ile tahmin etmektedir. Sonuçlar, damlatıcı debisi arttıkça 2B kesit alanının da arttığını göstermektedir.

Sonuç: Bu çalışmanın sonuçları, önerilen modelin ıslatma deseninin genel şeklini tanımladığını ve desenin ıslatma yarıçapı, maksimum ıslatma derinliği ve kesit alanını belirlemek için kullanılabileceğini göstermiştir.

INTRODUCTION

Drip irrigation is considered worldwide as a way to sustainably utilize deficit resources in irrigation applications. On the other hand, emitter discharge, irrigation time and soil hydraulic properties are not sufficiently considered in the design and management of drip irrigation systems. Several studies have been conducted for analytical (Philip, 1984; Chu, 1994), numerical (Lazarovitch et al., 2007) or empirical (Zur, 1996; Sepaskhah & Chitsaz, 2004; Amin & Ekhmaj, 2006; Elmaloglou & Malamos, 2006; Molai et al., 2008; Thabet & Zayani, 2008; Dabral et al., 2012) formulations to describe the shape of the wetting pattern and to estimate its components.

The wetting pattern is one of the main variables in the design and management of a drip irrigation system. The dimensions of the pattern are critical for choosing the appropriate spacing between the laterals and for choosing the correct spacing between emitters. Elmaloglou & Diamantopoulos (2007) carried out a study on a cylindrical flow model. In this study, two types of soils and two discharges were used. The vertical component of the wetting pattern was studied for pulse irrigation and continuous irrigation. The difference between the irrigation applications was eliminated for longer time. Bhatnagar & Chauhan (2008) devised a numerical model in order to to estimate the wetting pattern under an emitter. The spheroidal coordinate system was considered in the modeling. The results were evaluated comparatively with different solution approaches. Tian et al. (2011) devised a numerical model for the two-dimensional movement of water in a drip irrigation system. The 2D Richards equation was used to describe the movement of water in soil. The model was evaluated for the simulation of water movement in soil for the long-term water application conditions.

Drip irrigation is used in many arid and semi-arid regions. If the system is well designed and properly operated, high efficiency of water application and high crop yields can be achieved. Soil moisture distribution patterns were predicted by using the neutron scattering technique for the surface and subsurface drip irrigation conditions in the investigation carried out by Badr & Abuarab (2013). Soil moisture distribution was evaluated as a function of variation in the distance between the distributors and lateral pipes. A neutron moisture meter was used to measure soil moisture. The results indicate that the distribution of soil moisture and its uniformity under the surface emitters was highly influenced by the distance between the emitters and less by the lateral pipes. Kuklik & Dai Hoang (2014) determined the geometry of wetted soil volume under surface drip irrigation. The infiltration of water under an emitter and the spatial distribution of water in the soil profile are the main components of the model. The experiments were carried out for different emitter discharges and irrigation periods. The width and depth of the wetting pattern were determined. However, most of the evaluations were carried out using the plots for different conditions rather than the mathematical formulation. The equidistant line sources were used by Elmaloglou et al. (2013) for the simulation of soil water dynamics under surface drip irrigation. In this model, the two-dimensional distribution process was considered. The soil water distribution patterns were investigated for two soil types and two different emitter discharge. The results of the numerical model showed that the soil water dynamics mainly depend on the hydraulic properties of the soil, the distance between the drip lines and the irrigation depth.

The infiltrated water in the soil under a surface emitter forms a wetted zone whose shape resembles a semi-ellipse or a truncated sphere, depending on the total amount of applied water, emitter discharge and the hydraulic properties of the soil. Moncef & Khemaies (2016) devised an approach to estimate the wetted soil volume for a drip irrigation system. It was assumed that the wetting pattern has a semi-elliptical shape whose diagonals are merged with the soil surface and the axis of symmetry. The initial water content, the hydraulic conductivity of the soil and the water content in the wetting pattern are some of the components of the model. The study was conducted on three soil types. It was found that the predicted values were close to the results of the Healy & Warrick (1988) model. Kilic (2020) developed a model that enabled the prediction of the 3D volume wetting pattern under an emitter. The wetted soil volume was modeled. Al-Ogaidi et al. (2016) carried out an investigation for drip irrigation with two discharge rates and two soil textures. The vertical and horizontal progress of the wetting pattern was estimated by an empirical model for different application times. The depth of the wetting pattern and the wetting radius at the soil surface were estimated. The same procedure was used to estimate the shape of the wetting pattern.

The aim of this study is to develop models that determine the 2D cross-sectional area of the wetting pattern, the wetting radius and maximum wetting depth that occur under a surface emitter with different discharges at each time t of the water application period.

MATERIALS and METHODS

Experimental procedures

This research was conducted in the Department of Agricultural Engineering and Technologies at Faculty of Agriculture at Ege University. Details of the emitter discharge experiments were described in the investigation carried out by Demir et al. (2019). Emitters with discharges of 1.2, 1.7, 2.6, 3.0 and 4.0 L h^{-1} at a working pressure of 1.0 bar were used in the experiments.

The properties of the soil used for the experiment are listed in Table 1. The initial moisture content of the soil was 4-6%, as indicated by the pre-irrigation analysis.

Table 1. The properties of the soil used for the experiments

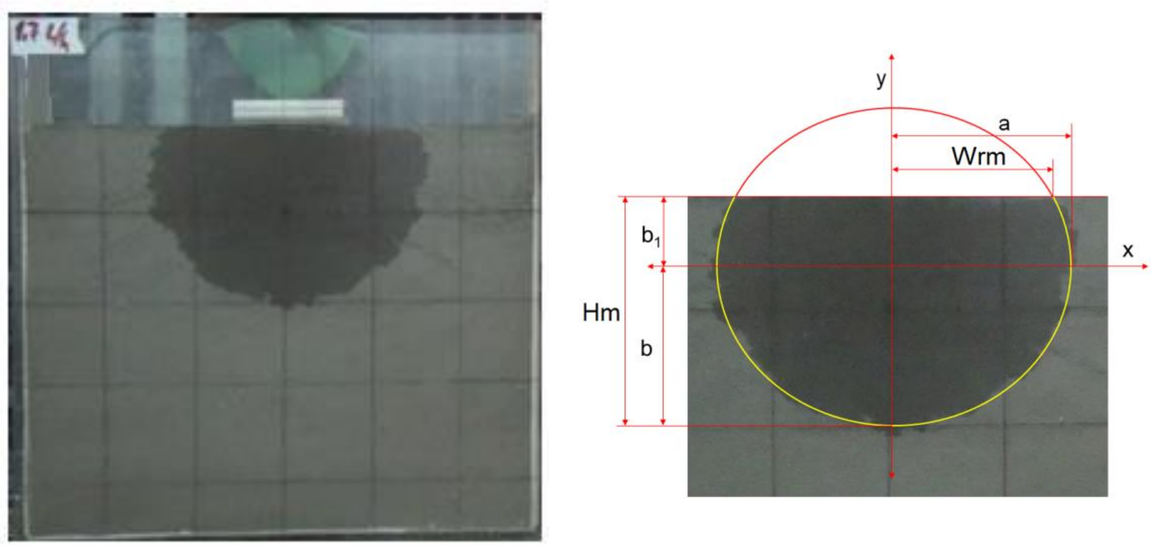
***Çizelge 1**. Denemelerde kullanılan toprak özellikleri*

Texture	Loamy sand
pH	7.72
Salt (%)	0.015
Lime (%)	3.3
Organic material (%)	0.81
Sand (%)	77.12
Silt (%)	16
Clay (%)	6.88
Moisture holding capacity (%)	30.11

Transparent Plexiglas containers 60x60x10 cm were used to determine the water distribution in the soil. Grid lines were drawn at 10 cm intervals on the outside of the boxes so that water movement in the soil could be easily observed. During the experiments, the dried soil samples were homogeneously filled into the Plexiglas containers and the top of the soil samples were smoothed. The water was applied through the emitters in the center of the top of the containers and the water movement was observed during the experiments.

Development of models to estimate the parameters of the wetting pattern

The real-time video recordings were recorded for each experiment during the period of water application (Figure 1a). The video recordings were converted to images with an interval of five minutes. It can be seen that the soil profile wetted by the emitters was fitted to an ellipse. This output was used to measure the baseline data associated with an ellipse on the images of the soil profiles wetted by each emitter (Figure 1b).



a b

Figure 1. a) Observation of the wetting pattern, b) Main parameters of the wetting pattern.

Şekil 1. *a) Islatma deseninin gözlenmesi, b) Islatma deseninin ana parametreleri.*

In this study, four main parameters were considered in defining the 2D pattern that occurs under an emitter. These are the wetting radius, the wetting depth and width and their distance from the soil surface. These parameters define the overall pattern that occurs in a drip irrigation system.

The 2D pattern under a surface emitter is simulated as a truncated ellipse (Figure 1b). The reason for this is that the maximum wetting width almost always occurs below the soil surface. Apart from this, the shape of the ellipse has a practical use in the application. This is another reason why the wetting pattern was simulated in this shape.

The main general shape representing the wetting patterns occurring in the experiments is shown schematically in Figure 2.

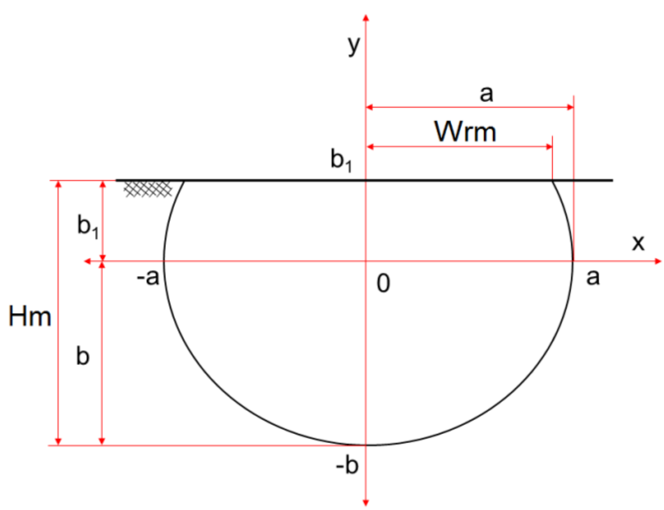


Figure 2. Simulation of the 2D wetting pattern, which becomes a truncated ellipse under a surface emitter.

Şekil 2. *Damlatıcı altında oluşan ıslatma deseninin kesik elips şeklinde 2B simülasyonu.*

The center of the ellipse in Figure 1 is the origin and the major axis is the x-axis. If you set up the equation for the central ellipse, you get equation (1).

$$x^2 = a^2\left(1 - \frac{1}{b^2}y^2\right) \tag{1}$$

In Figure 1, the area surrounded by the points –b, b1, Wr and a forms the cross-section. The cross-sectional area surrounded by these points is given by equation (2).

$$A = \int_{-b}^{b1} a\sqrt{\left(1 - \frac{y^2}{b^2}\right)}\,dy \tag{2}$$

If equation (2) is rearranged, the cross-sectional area of the pattern is obtained by carrying out equation (3) as follows.

$$A = a\left(\frac{b^2 \arcsin\left(\frac{b_1}{b}\right) + b_1\sqrt{b^2 - b_1^2}}{2b} + \frac{\pi b}{4}\right) \tag{3}$$

Y is also the symmetry axis of the 2D wetting pattern (Figure 2). The area of the entire 2D wetting pattern under an emitter can be determined by equation (4).

$$Ae = 2xA \tag{4}$$

The meaning of the symbols used in the equations and shown in Figure 2 is as follows. a is the maximum wetting radius (cm); b is the distance between the maximum wetting radius and the depth (cm); b1 is the distance from the maximum wetting radius to the soil surface (cm); A is the cross-sectional area of the right side of the wetting pattern with respect to the symmetry axis (cm^2); Ae is the experimental cross-sectional area of the entire pattern under an emitter (cm^2), Wrm is the measured wetting radius on the soil surface (cm) and Hm is the measured maximum wetting depth from the soil surface (cm).

Equation (3) and equation (4) provide a solution for the case where the value of the parameter b1 is zero. In this condition, the maximum wetted width corresponds to the diameter at the soil surface.

In the next step of the investigation, the sizes of the cross-sectional areas of the wetting patterns are defined as a function of time and the emitter discharge. In addition, the wetting radius and the maximum wetting depth that occur under a surface emitter with different discharges at each time t of the irrigation period are estimated by the numerical models developed in this study (equations 4, 6 and 7).

RESULTS and DISCUSSION

The temporal variations of wetting radius and maximum wetting depth with five different emitter discharges are shown in Figure 3.

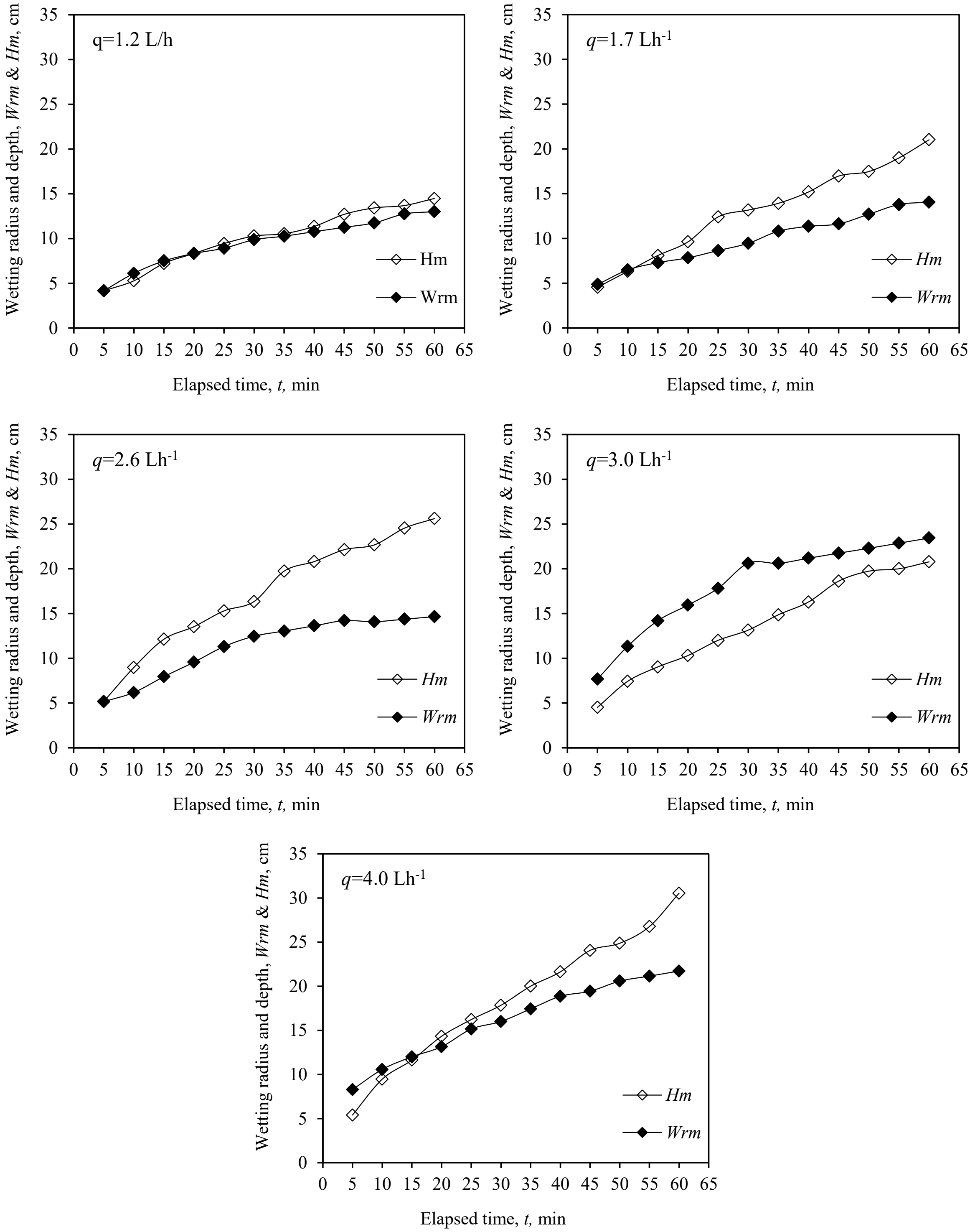


Figure 3. Temporal variations of the wetting radius and maximum wetting depth of the 2D wetting patterns occurring under different emitter discharges.

Şekil 3. *Farklı damlatıcı debilerinde meydana gelen 2B ıslatma desenlerinde ıslatma yarıçapı ve maksimum ıslatma derinliğinin zamansal değişimi.*

The wetting radius and maximum wetting depth show an increase as a function of time of water application in 2D wetting patterns occurring under different emitter discharges (Figure 3). The cross-sectional areas of the wetting patterns under different emitter discharges according to equation (4) are shown in Figure 4.

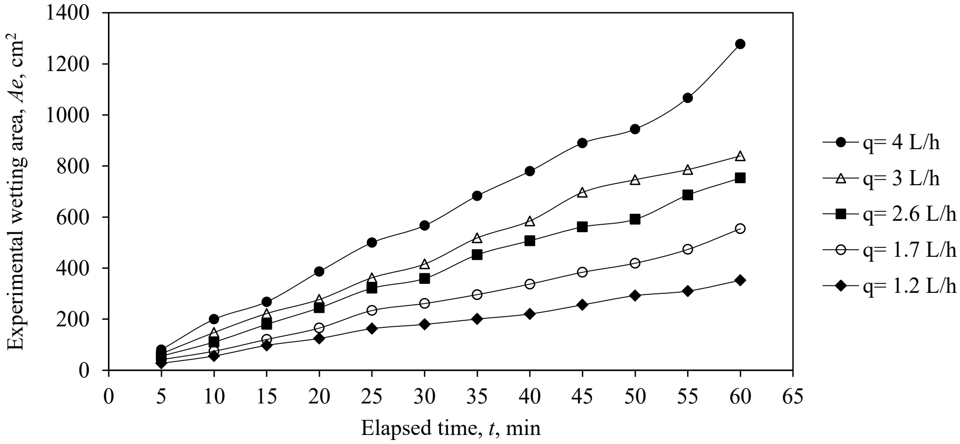


Figure 4. Temporal variations of the experimental cross-sectional areas of the wetting patterns occurring under different emitter discharges according to equation (4).

Şekil 4. *Eşitlik (4)'e göre farklı damlatıcı debilerinde meydana gelen ıslatma desenlerinde deneysel kesit alanlarının zamansal değişimi.*

The experimental cross-sectional areas of the wetting patterns occurring under the emitter discharges of 1.2, 1.7, 2.6, 3.0 and 4.0 L h^{-1} took the values of 352.35 cm^2, 554.29 cm^2, 752.91 cm^2, 839.30 cm^2 and 1278.02 cm^2 at the end of the 60 min water application, respectively (Figure 4). The increase in emitter discharge also increases the cross-sectional areas of the wetting patterns (Figure 4). These results are consistent with the findings of Al-Ogaidi et al. (2016).

Equation (5) applies to the total emitter discharges and the water application periods in this study. The equation is given below;

$$Ap = 4.3188\ q^{1.0045}\ t^{1.0316} \qquad R^2 = 0.995 \qquad (5)$$

In equation (5), Ap is the predicted area of the pattern (cm^2) occurring at time t of the water application period. q is the emitter discharge (L h^{-1}). t is an arbitrary time (min) during the water application period for estimating the area of the pattern.

Comparison between the experimental and predicted cross-sectional area of the wetting pattern occurring at any time t are shown in Figure 5.

The experimental and predicted areas of the pattern (Ae and Ap) were compared. The model provides satisfactory results within the range of operating and emitter discharges used in the experiments. As can be seen in Figure 5, a good agreement between Ae and Ap is obtained with a coefficient of determination of 0.995 between 5 and 60 minutes. The results show that the model given in equation (5) can be used to estimate the areas of the wetting patterns that occur at different emitter discharges at each time t of the water application period. In this way, an water application period compatible with the cross-section of the wetting pattern and the root zone of the plants can be determined. This also allows optimal planning of the irrigation timing.

In addition, the radius of wetting at the soil surface is predicted using the following equation (6).

$$Wrp = -132.3 + 273.6\,q - 198.2\,q^2 + 59.8\,q^3 - 6.29\,q^4 + 0.388\,t - 0.003\,t^2 \qquad (6)$$

R^2=0.961

Good agreement was obtained between the measured and predicted values of the wetting radius with the coefficient of determination 0.961 between 5 and 60 minutes (Figure 6). The results show that the solution approach developed in this study can be used to estimate the wetting radius that occurs at any time t during the water application period.

Furthermore, the maximum wetting depth that occurs under a surface emitter with different discharges is predicted by applying equation (7).

$$Hp = 90.34 - 198.82\,q + 149.39\,q^2 - 45.18\,q^3 + 4.74\,q^4 + 0.435\,t - 0.002\,t^2 \qquad (7)$$

R^2=0.947

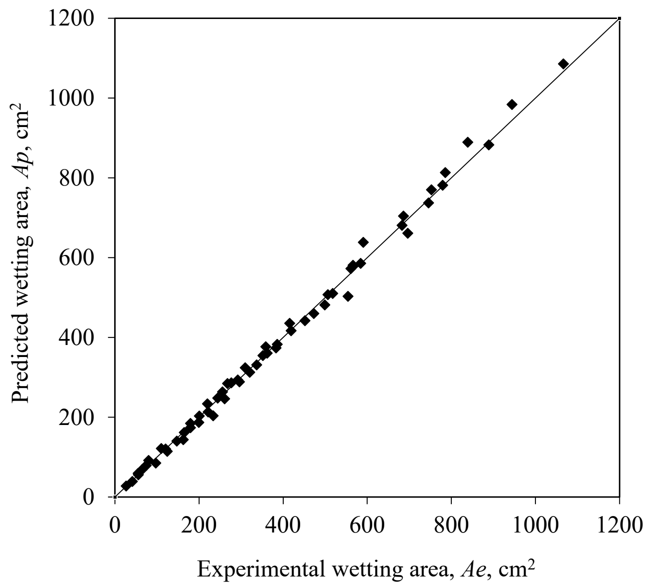


Figure 5. Comparison between the experimental and predicted wetting area.

Şekil 5. *Deneysel ve tahmin edilen ıslak kesit alanı büyüklüklerinin karşılaştırılması.*

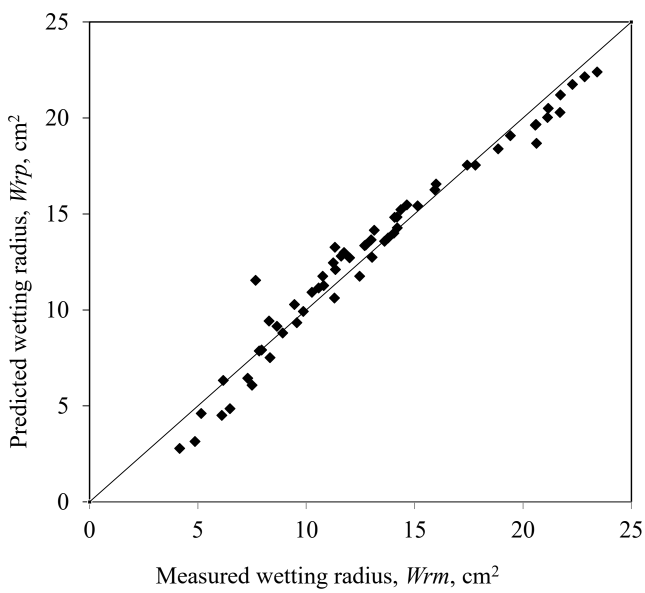


Figure 6. Comparison between the measured and predicted wetting radius.

Şekil 6. *Ölçülen ve tahmin edilen ıslatma yarıçaplarının karşılaştırılması.*

The measured and predicted values of maximum wetting depth were found to be compatible with each other with a coefficient of determination of 0.947 for each time t of the water application period between 5 and 60 minutes. This agreement is valid for the whole emitter discharges which were used in the experiments (Figure 7). These results indicate that the model proposed in this study can be used to estimate the maximum wetting depth for each time t of the water application time under a surface emitter. This method can be used for optimum irrigation timing for drip irrigation systems.

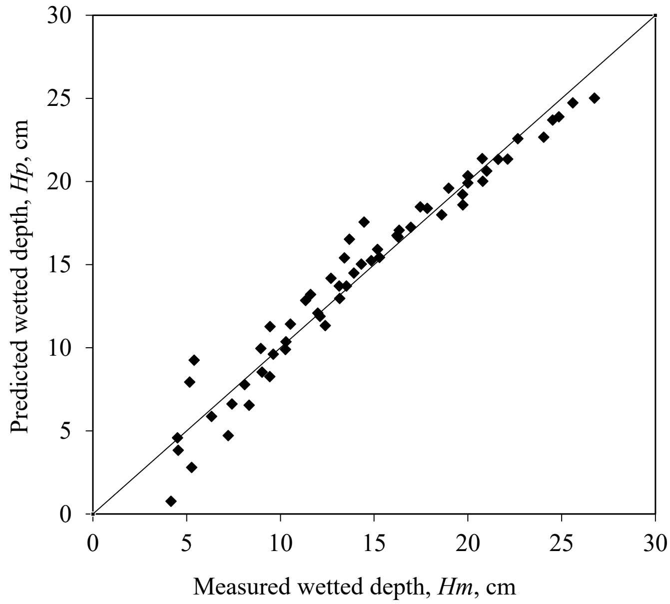


Figure 7. Comparison between the measured and predicted wetting depth.

Şekil 7. *Ölçülen ve tahmin edilen ıslatma derinliklerinin karşılaştırılması.*

A study was conducted by Bhatnagar & Chauhan (2008) to predict the components of the wetting pattern under a surface emitter. A numerical modeling approach was used. A time-dependent varying wetting radius was considered. The model was verified by the results of the investigation conducted by Bresler (1978) and Taghavi et al. (1984) . When the numerical model developed by Bhatnagar & Chauhan (2008) was run for q_1=2100 cm^3 h^{-1} and q_2=3300 cm^3 h^{-1} discharges, the advance of the water front up to the radial distance (r) was estimated well. However, higher values were estimated by the model for the higher values of r than those observed. The reason for this situation was explained that it could be the edge effects in the experiments. In the present study, the cross-sectional areas of the wetting patterns that occurred under the 1.7, 2.6, 3.0 and 4.0 L s^{-1} emitter discharges showed increases as a function of the increase in discharge and water application time (Figure 4). In addition, by conducting the experiments for a larger number of emitter discharges, the changes in the magnitudes of the wetting pattern parameters could be observed in more detail (Figure 3). The areas of the wetting patterns as a function of time, the wetting radius on the soil surface and the wetting depth for each emitter discharge for each time t of the water application period can be estimated by the numerical models developed in this study (Figures 5, 6 and 7). High coefficients of determination for these parameters (0.995, 0.961 and 0.947) were obtained by the proposed model in this investigation. These findings show that the models developed in the study can be used to predict the values of the components of the pattern for each time t of the water application time for different emitter discharges. In this way, the most appropriate time for water application can be determined that provides the closest match between the pattern and the plant root zone. This is of great benefit for the optimal design and operation of drip irrigation systems and for planning the timing of irrigation.

Al-Ogaidi et al. (2016) conducted a study to estimate the wetting pattern that occurs under a surface drip irrigation system using an empirical model. When the emitter discharge was increased from 3 L h^{-1} to 4.5 L h^{-1}, the wetting radius and wetted depth also increased by 9.81% and 19.09%, respectively. The extent of the wetting pattern in the profiles with sandy soils were higher than that in the profiles with clayey soils, as the fine-textured soils can store more water than the coarse-textured soils. This delays the horizontal and vertical advance of water in fine-textured soils. These results are in general agreement with the results of Li et al. (2007). Moncef et al. (2002) used three different emitter discharges in the laboratory experiments conducted on silty soils. Li et al. (2003) conducted laboratory experiments on loamy soils for a range of emitter discharges. It was found that the model proposed by Al-Ogaidi et al. (2016) gave good results in the studies presented above. The proposed model underestimated the wetting diameter. In addition, a different value for the wetting depth was determined than in the previous studies. The reason given for these results was that the previous experiments had been carried out under completely different conditions. In the present study, the area of the whole wetting pattern is determined by a mathematical model. This solution technique is important because it ensures compatibility between the cross-section of the root zone and the wetting pattern in the soil profile under a surface emitter. In this way, a wetting pattern can be determined that is suitable for the development of the crop's root zone.

The previous empirical models developed by Schwartzman & Zur (1986), Malek & Peters (2011), Amin & Ekhmaj (2006), Al-Ogaidi et al. (2015) and Naglič et al. (2014) estimated only two points of the wetting pattern: the wetting diameter at the soil surface and the wetted depth. In contrast, the model proposed by Al-Ogaidi et al. (2016) also estimated the maximum wetting width that occurred below the soil surface in addition to these two points, but no model was developed. In the present study, the model in equation (5) was developed, which estimates the area of the total wetting pattern that occurs at each time t of the irrigation application time (Figure 5). Since the – previously mentioned parameters defining the overall wetting pattern are considered in this process, more accurate results are obtained. Thus, both the main shape representing the 2D wetting patterns that occur under different irrigation conditions (Figure 1, Figure 2) and the area of the overall wetting pattern are estimated. In addition, the wetting radius and maximum wetting depth are estimated by the numerical models developed in this study (equations 6 and 7). The results show that the area of the wetting pattern, the wetting radius and the maximum wetting depth can be estimated by the models proposed in this study. High coefficients of determination confirm these results for these parameters.

Consequently, it is possible to obtain a pattern that is suitable in shape and size with the root zone of the crop, which shows temporal variations depending on the growth stage of the plants. The results of this study show that the models proposed in this investigation can be used to estimate the cross-sectional area of the 2D pattern, the wetting radius and the maximum wetting depth that occur under a surface emitter with different discharges for each time t of the water application period.

CONCLUSION

In this study, the principal shape representing the 2D wetting patterns occurring under the 1.2, 1.7, 2.6, 3.0, and 4.0 L h^{-1} discharges of the surface emitter under uniform soil profile conditions was defined (Figure 1, Figure 2), and the area of this pattern was determined by an analytical solution method (equations 3 and 4). The parameters of the wetting radius, the maximum wetting depth and the maximum wetting width in the soil profile, and the depth of this maximum wetting width from the soil surface allow the overall wetting pattern to be defined. The cross-sectional areas of the wetting patterns showed an increase as a function of the increases in emitter discharges (Figure 4). These results are consistent with the movement characteristics of the water under the surface emitter. In addition, the wetting radius, wetting depth and cross-sectional area of the wetting pattern were estimated for each time t of the water application period for all emitter discharges used in the experiments by the numerical models developed in this study. High coefficients of determination (0.961, 0.947 and 0.995) were obtained for the above parameters.

The results of this study show that the proposed models can be used to estimate the cross-sectional area of 2D pattern, wetting radius and wetting depth that occur under a surface emitter with different discharges for each time t of the water application period. In this way, a contribution is made to improving the optimal design and management of drip irrigation systems.

Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: VD, MK, HY, MN, RCA; sample collection: VD, MK, HY, MN, RCA; analysis and interpretation of data: VD, MK, HY, MN, RCA; statistical analysis: VD, MK, HY, MN, RCA; visualization: VD, MK, HY, MN, RCA; writing manuscript: VD, MK, HY, MN, RCA.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

We declare that there is no need for an ethics committee for this research.

Financial Support

This study did not receive funding from any organisation.

Article Description

This article was edited by Section Editor Dr. İlkay ALKAN.

REFERENCES

Al-Ogaidi, A.A.M., A. Wayayok, M. R. Kamal & A.F. Abdullah, 2015. A modified empirical model for estimating the wetted zone dimensions under drip irrigation. Jurnal Teknologi, 76 (15): 69-73. https://doi.org/10.11113/jt.v76.5954

Al-Ogaidi, A.A.M., A. Wayayok, M.K. Rowshon & A.F. Abdullah, 2016. Wetting patterns estimation under drip irrigation systems using an enhanced empirical model. Agricultural Water Management, 176: 203-213. https://doi.org/10.1016/j.agwat.2016.06.002

Amin, M.S. & A.I. Ekhmaj, 2006. "DIPAC-drip irrigation water distribution pattern calculator, 503-513". In: 7th International Micro Irrigation Congress, (13-15 September 2006, Kuala Lumpur, Malaysia) 1016 pp.

Badr, A.E. & M.E. Abuarab, 2013. Soil moisture distribution patterns under surface and subsurface drip irrigation systems in sandy soil using neutron scattering technique. Irrigation Science, 31 (3): 317-332. https://doi.org/10.1007/s00271-011-0306-0

Bhatnagar, P. & H. Chauhan, 2008. Soil water movement under a single surface trickle source. Agricultural Water Management, 95 (7): 799-808. https://doi.org/10.1016/j.agwat.2008.02.003

Bresler, E., 1978. Analysis of trickle irrigation with application to design problems. Irrigation Science, 1 (1): 3-17. https://doi.org/10.1007/BF00269003

Chu, S.T., 1994. Green-Ampt analysis of wetting patterns for surface emitters. Journal of Irrigation and Drainage Engineering, 120 (2): 414-421. https://doi.org/10.1061/(ASCE)0733-9437(1994)120(1994)120:2(414)

Dabral, P., P. Pandey, A. Pandey, K. Singh & M.S. Singh, 2012. Modelling of wetting pattern under trickle source in sandy soil of Nirjuli, Arunachal Pradesh (India). Irrigation Science, 30 (4): 287-292. https://doi.org/10.1007/s00271-011-0283-3

Demir, V., H. Yürdem, A. Yazgi & T. Günhan, 2019. Effect of different pipe wall thicknesses on flow rate of cylindrical type integrated emitters used in drip irrigation pipes, Journal of Agriculture Faculty of Ege University, 56 (2): 213-220. https://doi.org/10.20289/zfdergi.485854

Elmaloglou, S. & E. Diamantopoulos, 2007. Wetting front advance patterns and water losses by deep percolation under the root zone as influenced by pulsed drip irrigation. Agricultural Water Management, 90 (1-2): 160-163. https://doi.org/10.1016/j.agwat.2007.02.005

Elmaloglou, S. & N. Malamos, 2006. A methodology for determining the surface and vertical components of the wetting front under a surface point source, with root water uptake and evaporation. Irrigation and Drainage: The journal of the International Commission on Irrigation and Drainage, 55 (1): 99-111. https://doi.org/10.1002/ird.220

Elmaloglou, S., K.X. Soulis & N. Dercas, 2013. Simulation of soil water dynamics under surface drip irrigation from equidistant line sources. Water Resources Management, 27 (12): 4131-4148. https://doi.org/10.1007/s11269-013-0399-8

Healy, R. & A. Warrick, 1988. A generalized solution to infiltration from a surface point source. Soil Science Society of America Journal, 52 (5): 1245-1251. https://doi.org/10.2136/sssaj1988.03615995005200050006x

Kilic, M., 2020. A new analytical method for estimating the 3D volumetric wetting pattern under drip irrigation system. Agricultural Water Management, 228 (105898): 1-12. https://doi.org/10.1016/j.agwat.2019.105898

Kuklik, V. & T. Dai Hoang, 2014. Soil moisture regimes under point irrigation. Agricultural Water Management, 134: 42-49. https://doi.org/10.1016/j.agwat.2013.11.012

Lazarovitch, N., A. Warrick, A. Furman & J. Simunek, 2007. Subsurface water distribution from drip irrigation described by moment analyses. Vadose Zone Journal, 6 (1): 116-123. https://doi.org/10.2136/vzj2006.0052

Li, J-S., H-Y. Ji, L. Bei & Y-C. Liu, 2007. Wetting patterns and nitrate distributions in layered-textural soils under drip irrigation. Agricultural Sciences in China, 6 (8): 970-980. https://doi.org/10.1016/S1671-2927(07)60136-9

Li, J., J. Zhang & L. Ren, 2003. Water and nitrogen distribution as affected by fertigation of ammonium nitrate from a point source. Irrigation Science, 22 (1): 19-30. https://doi.org/10.1007/s00271-003-0064-8

Malek, K. & R. T. Peters, 2011. Wetting pattern models for drip irrigation: new empirical model. Journal of Irrigation and Drainage Engineering, 137 (8): 530-536. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000320

Molai, K.M., A.A.M. Liaghat & F. Abbasi, 2008. Estimating soil moisture pattern in subsurface drip irrigation using dimensional analysis method. Iranian Journal of Agricultural Sciences 39 (2): 371-378.

Moncef, H. & Z. Khemaies, 2016. An analytical approach to predict the moistened bulb volume beneath a surface point source. Agricultural Water Management, 166: 123-129. https://doi.org/10.1016/j.agwat.2015.12.020

Moncef, H., D. Hedi, B. Jelloul & M. Mohamed, 2002. Approach for predicting the wetting front depth beneath a surface point source: theory and numerical aspect. Irrigation and Drainage: The Journal of the International Commission on Irrigation and Drainage, 51 (4): 347-360. https://doi.org/10.1002/ird.60

Naglič, B., C. Kechavarzi, F. Coulon & M. Pintar, 2014. Numerical investigation of the influence of texture, surface drip emitter discharge rate and initial soil moisture condition on wetting pattern size. Irrigation Science, 32 (6): 421-436. https://doi.org/10.1007/s00271-014-0439-z

Philip, J., 1984. Travel times from buried and surface infiltration point sources. Water Resources Research, 20 (7): 990-994. https://doi.org/10.1029/WR020i007p00990

Schwartzman, M. & B. Zur, 1986. Emitter spacing and geometry of wetted soil volume. Journal of Irrigation and Drainage Engineering, 112 (3): 242-253. https://doi.org/10.1061/(ASCE)0733-9437(1986)112:3(242)

Sepaskhah, A. R. & H. Chitsaz, 2004. Validating the green-ampt analysis of wetted radius and depth in trickle irrigation. Biosystems Engineering, 89 (2): 231-236. https://doi.org/10.1016/j.biosystemseng.2004.06.011

Taghavi, S.A., M.A. Mariño & D.E. Rolston, 1984. Infiltration from trickle irrigation source. Journal of Irrigation and Drainage Engineering, 110 (4): 331-341. https://doi.org/10.1061/(ASCE)0733-9437(1984)110:4(331)

Thabet, M. & K. Zayani, 2008. Wetting patterns under trickle source in a loamy sand soil of south Tunisia. American-Eurasian Journal of Agricultural & Environmental Sciences, 3 (1): 38-42.

Tian, F., L. Gao & H. Hu, 2011. A two-dimensional Richards equation solver based on CVODE for variably saturated soil water movement. Science China Technological Sciences, 54 (12): 3251-3264. https://doi.org/10.1007/s11431-011-4566-y

Zur, B., 1996. Wetted soil volume as a design objective in trickle irrigation. Irrigation Science, 16 (3): 101-105. https://doi.org/10.1007/BF02215617