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Research Article

Modelling of wetting patterns for surface drip irrigation in dense clay soil

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Abstract
The proportion of agricultural water consumption is continuously decreasing due to increased competition for water resources by urban, industrial, and agricultural users. Drip irrigation is more efficient in terms of water and energy utilization. These considerations are critical in view of the ongoing struggle for water resources among various consumers due to water scarcity. Some of the most critical criteria in the effective design and maintenance of drip irrigation systems are the shape and size of the volume of wet soil beneath the emitter. Hence several statistical models were constructed in this research to estimate the dimensions of wetting patterns, which are critical for designing an optimal drip irrigation system. The Nash-Sutcliffe efficiency (NSE), coefficient of correlation (CC), and root mean square error (RMSE) criteria were used to assess the models' performance. The results showed that the Polynomial model was the most accurate for horizontal advance, with 0.94, 0.93, and 1.33 (cm) values for CC, NSE, and RMSE, respectively. For vertical advance, the logarithmic model showed 0.96, 0.96, and 0.72 (cm) values for CC, NSE, and RMSE. Thus, in the absence of a wetting pattern and under identical conditions, these models can be utilized to generate synthetic horizontal and vertical advances data.

Keywords: Wetted radius, Wetted depth, Water distribution, Wetted pattern and drip irrigation

INTRODUCTION

Climate change is more responsive to agricultural demand, particularly for irrigation water. A change in the climate at the field level may modify the demand for and timing of irrigation. Higher dryness may lead to increased demand, but demand may be lowered if soil moisture content rises during important times of the year (Alejo *et al*., 2021). Most irrigated areas in India are expected to demand more water around 2025, and global net irrigation requirements are expected to rise by 3.5–5 percent by 2025, and 6–8 percent by 2075, compared to the case without climate change. One of the most efficient ways for irrigating crops, vegetables, and fruit trees is surface drip irrigation. Drip irrigation systems with the best design should distribute water evenly between the emitters and laterals. The soil hydraulic qualities, the spacing and depth of emitters and laterals, and the emitters discharge all significantly impact water distribution. Drip irrigation systems can be designed, installed, and managed using a variety of models that explain infiltration from a point/line source

(Singh *et al*., 2006). Some analytical, numerical, empirical and statistical models have been created to predict wetting zone dimensions for surface drip irrigation from a point source. Analytical and numerical models commonly solve governing flow equations for certain initial and boundary conditions, whereas empirical models are frequently constructed by regression analysis of field measurements (Ghumman *et al*., 2018). Lazarovitch *et al*. (2007) proposed a moment analysis approach to describe spatial and temporal subsurface wetting patterns for irrigation from surface drip irrigation systems, which was a novel approach. Samadianfard *et al*. (2012) took a somewhat different strategy, introducing genetic programming to anticipate wetting patterns.

Cook *et al*. (2003) created a user-friendly software programme that uses analytical methods to estimate the wetting pattern for various soil hydraulic parameters, emitter placements, and water quantities delivered to homogeneous soils from a surface or subsurface point source. HYDRUS-2D (Simunek *et al*., 1999) is a well-known Windows-based computer software package that simulates water, heat, and/or solute flow in two-dimensional, variably saturated porous surfaces using numerical methodologies. Several researchers tested this software to see how well it could imitate water movement from a surface and subsurface drip irrigation system. Lazarovitch *et al*. (2005) added a new, system-dependent boundary condition to HYDRUS-2D that considers source characteristics, inlet pressure, and the impact of soil hydraulic properties on predicted subsurface source discharge and tested the code against transient experimental data. Cook *et al*. (2003) used WetUp and HYDRUS-2D to examine wetting patterns estimated for surface and subsurface drip irrigation systems. This was a completely theoretical study that did not use any observational data. Cook *et al*. (2003) discovered that both models produced identical findings for fine-textured soils. It's worth noting that models based on analytical and numerical solutions of the governing flow equation don't always produce the same results. Lazarovitch *et al*. (2005) added a new, system-dependent boundary condition to HYDRUS-2D that takes into account source characteristics, inlet pressure, and the impact of soil hydraulic properties on predicted subsurface source discharge and tested the code against transient experimental data. Moncef & Khemaies (2016) developed an analytical method for determining the volume of wet soil beneath a drip emitter. They compared the results of their analytical technique to those of their laboratory experiments and discovered that they were in good accord. They established an analytical method for estimating the wetted shape and volume with a single emitter. Samadianfard *et al*. (2012) used HYDRUS 2D software to mimic soil wetting patterns using genetic programming (GP). They used 12 distinct soil textures from the USDA-SCS soil texture triangle and variable emitter discharge and irrigation duration. Two distinct GP models were then explored utilizing the calculated depth and radius of the wetting pattern as target outputs. Finally, the ability of GP to simulate wetting patterns was investigated using data set values that were not used in training. According to the findings, the GP approach exhibited good agreement with the results. Several empirical methods for estimating the distance of the wetting front from a surface dripper have been proposed in the literature. For example, Schwartzman and Zur (1987) devised an empirical model to calculate the vertical and horizontal distances between a wetting front and a surface point source. Their empirical model was built based on field studies on two soil types (Gilat loam and Sinai sand). This model was tested by Amin and Ekhmaj (2015) using numerous experimental datasets, and it was modified by including the saturated soil water content as one of the model parameters. Finally, Kandelous and Šimůnek (2010) established an empirical model for predicting the distances from the wetting front to a subsurface point source in the upward, downward, and horizontal directions. This empirical model was created using data obtained in the lab using a subsurface dripper installed at a depth of 30 cm in clay loam soil. Al-Ogaidi *et al*. (2016) established empirical equations for estimating drip emitter wetting patterns, and the suggested model accurately predicts the entire wetting pattern and replicates published experimental data. Iqbal *et al*. (2017) used a standard sandbox model to develop empirical equations for the maximum wetted radius and depth based on a variety of variables such as emitter discharge, irrigation time, soil bulk density, hydraulic conductivity, initial and final soil moisture contents, and percentage of sand, silt, and clay in soil formation. With these parameters, the empirical equations functioned well and generated fair accuracy. According to the literature review, the wetted depth, width, and wetted volume of soil are among the most significant characteristics in drip emitter design (Arpna Bajpai and Arun Kaushal, 2020). Varying soils have different infiltration rates. It is vital to investigate the wetting pattern created by various emitter discharges in varied soils in order to conserve water and make the system more efficient. In addition, determining the correct emitter discharge for each soil is crucial in developing an effective drip irrigation system. The present study assessed the accuracy of these distinct statistical models for estimating wetness zone dimensions, compare their predictions to field data, and describe their specific merits and shortcomings in this work.

MATERIALS AND METHODS

The field experiments were carried out to collect information about the wetting pattern for surface drip irrigation as follows.

Measurement of Horizontal and Vertical Water Movement

The experiments were carried out at the Research Field of the Agricultural Engineering College and Research Institute of the Tamil Nadu Agricultural University, Tamil Nadu, India in the year 2021. The drip irrigation system with inline lateral having emitter spacing of 45 cm and discharge rate of 4 lph was installed in the field. System was initially operated under no crop conditions at different timings viz 10 min, 20 min, 30 min, 50 min, 60 min, 70 min, 80 min, 90 min, 100 min, 120 min and 140 min. At the end of each pre-decided time, the soil around the emitter was dug out, and the distance of the wetting front from the emitter was measured in the horizontal, vertical downward directions. Maximum distances between the wetting front and the emitter in particular directions (downward, and horizontal) were used and compared with various models. From the experiment data statistical models were developed for predicting soil water movement in this study were Exponential, Linear, Logarithmic, Polynomial and Power models. The best fit model was used to estimate wetting front advances in the inline drip irrigation system at different operation times by comparing horizontal and vertical water movement calculated by developed statistical models with observed water movement.

Statistical modelling

In a line source drip irrigation system, statistical models were used to determine the best wetting front model at various operation times. Exponential, Linear, Logarithmic, Polynomial, and Power models were utilized as statistical models.

Exponential Model

The exponential model, which is based on degrading failure process. The model developed one the basis of the following equation.

$$y = b\, e^{at}$$

……Eq. 1

Linear model

Linear models describe a continuous response variable as a function of one or more predictor variables. They can help you understand and predict the behaviour of complex systems or analyse experimental data.

$$y = \beta_0 + \Sigma\beta_i x_i + €_i$$

…….Eq.2

Logarithmic model

Logarithmic functions are the inverses of exponential functions. The inverse of the exponential function

$$y = log_a\, x$$

…….Eq.3

Polynomial model

Polynomial models are a great tool for determining which input factors drive responses and in what direction.

$$y = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_{11} x_1^2 + \alpha_{22} x_2^2 + \alpha_{12} x_1 x_2 + €$$

…….Eq.4

Power model

Power model involves taking logarithm of both the dependent and independent variable. The slope from the bivariate regression will produce the power.

$$y = ax^n$$

…….Eq.5

Where, *y* (also called the response) as a function of one or more independent variables x_i (called the predictors), *a* and *b* = parameters to be estimated by the regression method based on experimental data, β represents linear parameter estimates to be computed and ϵ represents the error terms.

Statistical analysis

Coefficient of correlation

The coefficient of correlation is a measure of the linear regression between the predicted values and the targets of models. The coefficient of correlation (CC) is computed as

$$C.C = \frac{Z\sum ab - (\sum a)(\sum b)}{\sqrt{Z\,(\sum a^2) - (\sum a)^2}\,\sqrt{Z\,(\sum b^2) - (\sum b)^2}}$$

…….Eq.6

Table 1. Soil physical properties of experimental plot

Soil characteristics	Particulars	Composition
Physical characteristics	Bulk Density, g cc^{-1}	1.312
	Field capacity, (per cent)	27.71
	Permanent wilting point, (per cent)	15.32
	Textural class	Clay loam

The range of correlation coefficient is: -1 to +1. Zero value indicates that there is no relation between the actual and predicted data.

Nash–Sutcliffe efficiency

The Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970) has value between - ∞ and 1. Its value is defined by

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{z}(a_i - b_i)^2}{\sum_{i=1}^{z}(a_i - \bar{a})^2} \quad \text{.......Eq.7}$$

When the value of NSE≥90%, it means that the performance of the model is a satisfactory performance, if value NSE lies between 80% and 90%, it means that the performance is fairly good, and a value ≤80% shows that the performance of the model is an unsatisfactory

performance.

Root mean square error (RMSE)

This method exaggerates the prediction error—the difference between prediction value and actual value. The root mean squared error (RMSE) is evaluated by

$$\mathrm{RMSE} = \sqrt{\frac{1}{z}\sum_{i=1}^{z}(a_i - b_i)^2} \quad \text{.......Eq.8}$$

where *a* is the calculated and *b* is observed values of infiltration rate and *z* is the number of observations.

The combined use of C.C, NSE and RMSE provides a sufficient evaluation of every models performance and favors a judgment of the precision of the five modelling approaches implemented in the current study.

RESULTS AND DISCUSSION

In present study, Table 2 and Table 3 show the proposed statistical models for both horizontal and vertical water movement progress. Statistical analysis determined the best suited model in both circumstances. Tables 4 and 5 show the outcomes of the statistical analysis criterion. According to the table, the Polynomial model was the most accurate for horizontal progress, with C.C, NSE, and RMSE values 0.94, 0.93, and 1.33 (cm). For vertical advance, a logarithmic model with CC, NSE, and RMSE of 0.96, 0.96, and 0.72 (cm) was the best fit.

The horizontal and vertical water movement observed in dense clay loam soil was compared to the horizontal and vertical water movement predicted by best fit statistical models plotted versus operating time. Fig. 3 and 4 show horizontal and vertical water movement predicted by statistical models compared to experimentally observed soil water movement. Figures show that horizontal and vertical soil water movement predicted by polynomial and logarithmic models at different operation times follow the same pattern as observed horizontal and vertical soil water movement. Rahul and Manikandan (2019) studied the wetting pattern in Kumulur, Tamil Nadu State and they showed that, polynomial models were good at generating synthetic wetting pat-

Table 2. Performance evaluation statistical models for the horizontal advance of water

Sr. No	Models	Coefficient of correlation (C.C)	Nash–Sutcliffe efficiency (NSE)	Root mean square error (RMSE) (cm)
1	Exponential	0.71	0.72	2.76
2	Linear	0.77	0.70	2.61
3	Logarithmic	0.90	0.90	1.65
4	Polynomial	0.94	0.93	1.33
5	Power	0.89	0.88	1.78

Table 3. Performance evaluation statistical models for the vertical advance of water

Sr. No	Models	Coefficient of correlation (C.C)	Nash–Sutcliffe efficiency (NSE)	Root mean square error (RMSE) (cm)
1	Exponential	0.84	0.84	1.67
2	Linear	0.89	0.88	1.32
3	Logarithmic	0.96	0.96	0.72
4	Polynomial	0.95	0.95	0.85
5	Power	0.95	0.95	0.85

Vertical advance measurement

Horizontal advance measurement

Fig. 1. *Measurement of vertical and horizontal advance of water in the experimental plot*

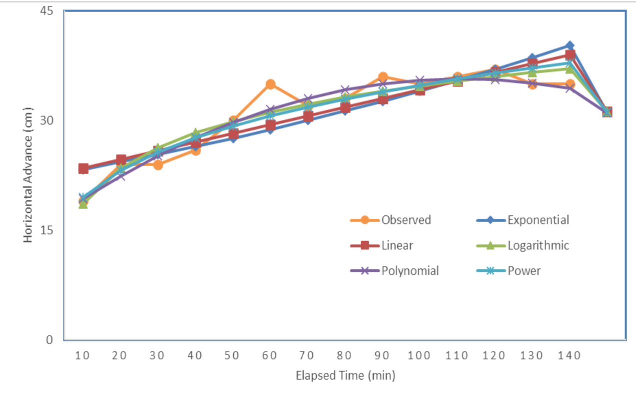

Fig. 2. *Comparison of observed wetting pattern in horizontal path with statistical models*

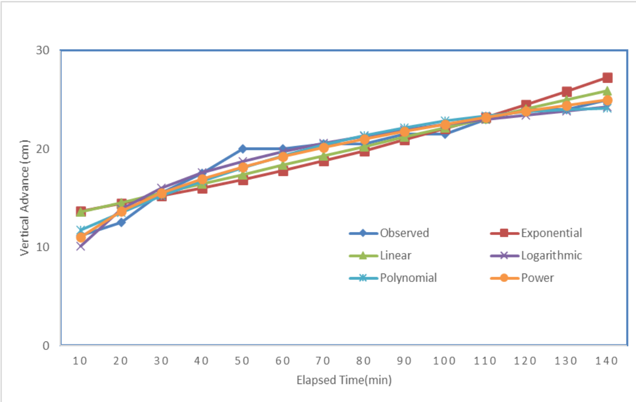

Fig. 3. *Comparison of observed wetting pattern in vertical path with statistical models*

terns. The close correlation between actual and expected data revealed that the prediction was accurate. When the operation duration was increased, the wetted radius grew as well, and the vertical wetting depth was greater than the horizontal wetting depth. Kyada & Munjarappa (2013) reported the similar results for clay loam soil, where wetted width increases rapidly at the start of irrigation, but the increase was found to be very slow later on. Similarly Salwa *et al*. (2010) also noted that, the vertical wetting front was found to be greater in sandy soil as compared with clayey soil (36.07% more), while the horizontal wetting front was found to be greater in clayey soil as compared with sandy soil (13.08% more). It ia also observed that in clayey soils, a higher emitter discharge rate favours both vertical and lateral water movement under drip irrigation. At a higher flow rate, soil moisture was higher, but at a lower discharge rate, soil moisture was lower. At a lower discharge rate, the wetted radius was larger. After irrigation, redistribution is nearly doubled in depth. However, the width of moist soil does not greatly increase. Many similar results were discussed and reported by Arpna and Arun (2020) in their review on water distribution under trickle irrigation.

Once the wetting front reaches the soil surface, downward water circulation intensifies in natural (field) conditions. Because statistical methods, such as the polynomial and logarithmic models, ignore this phenomenon and estimate each direction (i.e., horizontal and downward) independently, the observed downhill water movement was significantly faster than the statistical model predicted. Improving the present drip tubing boundary condition may be important, which specified a constant water flux during irrigation for soils with low hydraulic conductivity, fine-textured soils, or simulations with high water application rates. Significant positive pressure can develop around the drip tape as the earth becomes saturated while irrigating a low permeability soil. Therefore, the water flux should decrease rather than remain constant in response to the pressure buildup.

Table 4. Statistical model for horizontal water movement in dense clay soil

S. No	Model	Equation
1	Exponential	$y = 22.36e^{0.0042x}$
2	Linear	$y = 0.1198x + 22.231$
3	Logarithmic	$y = 7.022\ln(x) + 2.4104$
4	Polynomial	$y = -0.0016x^2 + 0.3557x + 15.94$
5	Power	$y = 10.868x^{0.2528}$

Where y = Horizontal advance (cm), x = Elapsed time (min)

Table 5. Statistical model for vertical water movement in clay soil

S.No	Model	Equation
1	Exponential	$y = 12.969e^{0.0053x}$
2	Linear	y = 0.0951x + 12.629
3	Logarithmic	y = 5.3505ln(x) – 2.1831
4	Polynomial	$y = -0.0007x^2 + 0.2001x + 9.8291$
5	Power	$y = 5.4233x^{0.3091}$

Where Y =Vertical advance (cm), X = Elapsed time (min)

Conclusion

In the present study, the horizontal soil water content distributions predicted using a polynomial model and the vertical soil water content distributions predicted using a logarithmic model match well with experimental data. The findings suggest using a polynomial model for horizontal water flow and a logarithmic model for vertical water flow as a tool for researching and planning drip irrigation management strategies. Based on the findings of the experiments, it was inferred that increasing irrigation volume increases horizontal and vertical water movement. The maximum horizontal and vertical water movement of two variables can be simulated using the proposed statistical models. The accuracy of the statistical models' results is satisfactory. The statistical models are data-driven and can only be used on soils similar to the ones for which the equations were built. The established model aids in calculating suitable emitter spacing, which lowers the cost of drip laterals.

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Conflict of interest

The authors declare that they have no conflict of interest.

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