Original Research Article

Enhancing Drip Irrigation Efficiency through Novel Statistical Modeling of Wetting Patterns in Water-Scarce Agriculture

ABSTRACT

Drip irrigation has emerged as a water and energy-efficient method amidst intensified competition for limited water resources in urban, industrial, and agricultural sectors. This study introduces novel statistical models for estimating critical wetting pattern dimensions in designing optimized drip irrigation systems. The logarithmic model shows precision in vertical advance with a CC of 0.98 and an RMSE of 0.76 cm. Additionally, The Polynomial model demonstrates exceptional accuracy in predicting horizontal advance, with a Coefficient of Correlation (CC) of 0.98 cm and a Root Mean Square Error (RMSE) of 1.25 cm respectively.These models offer valuable insights for efficient irrigation design, particularly in water-scarce conditions, enabling sustainable and precise water and nutrient distribution in agriculture. Embracing these models in irrigation planning can substantially enhance water use efficiency, effectively addressing the pressing challenges posed by water scarcity in agriculture and contributing to sustainable water management practices.

Keywords: Drip irrigation, wetting pattern, statistical models, water use efficiency, water scarcity, sustainable agriculture.

Introduction

Growing global population and climate impact demand sustainable agriculture. Precision techniques - irrigation, fertilization, genetics, agronomy - are vital. They enhance productivity, resource use, and resilience. However, overuse risks environmental and social harm. Misused inputs like nitrogen fertilizers lead to pollution. Precise management is essential. Irrigated agriculture uses 70% of global water, needing efficient approaches. Conventional methods waste water and pollute groundwater. Sustainable alternatives are crucial in India. Drip fertigation is notable, delivering water and nutrients directly to roots through emitters. Compared to traditional methods, drip irrigation excels in water efficiency, reducing losses. It optimizes fertilization, decreasing stress, hastening harvest, and improving quality. Its adoption boosts crop growth and overall productivity, benefiting water resources.According to Pourgholam, Amiji et al. (2020) the enhancement of crop productivity has a positive impact on water resources, indirectly leading to their increase. Moreover, they emphasized that improving water productivity serves as a viable strategy to conserve non-renewable water resources.There is no doubt that the adoption of drip irrigation has brought about revolutionary advantages.Efficient planning and design of a drip irrigation system are crucial for supplying the precise amount of water needed to the crops uniformly. The primary objective of the system's design is to determine the dimensions of its components in such a way that ensures the required water quantity is delivered with the desired uniformity while keeping the overall cost to a minimum. Achieving a nearly uniform water application to all plants in the field necessitates a well-designed irrigation system that maintains the desired hydraulic pressure in the pipe network and provides the required operating pressure at the emitter. Diverse models are available for designing, installing, and effectively managing drip irrigation systems, all of which revolve around understanding the process of infiltration from either a point or a line source. These models serve as valuable tools to optimize the design and performance of drip irrigation setups, ensuring efficient water distribution to crops and enhancing overall agricultural productivity. Various types of models, including analytical, numerical, empirical, and statistical approaches, have been developed to forecast the wetting zone dimensions in surface drip irrigation systems originating from a point source. Analytical and numerical models typically involve solving the governing flow equations with specific initial and boundary conditions. On the other hand, empirical models are constructed by conducting regression analyses on field measurements. These diverse modeling techniques provide valuable tools for accurately predicting and understanding the extent of the wetting zone, aiding in the efficient design and management of surface drip irrigation systems. (Ghumman et al., 2018). Numerous empirical approaches have been put forward in the existing literature to estimate the distance of the wetting front from a surface dripper. Various methods have been suggested and studied to determine the extent of water penetration in the soil around the dripper's location, offering valuable insights into the wetting pattern and distribution of water during surface drip irrigation. Schwartzman and Zur (1987) developed an empirical model to compute the vertical and horizontal distances between a surface point source and the wetting front. This model was derived from extensive field studies conducted on two distinct soil types, namely Gilat loam and Sinai sand. Amin and Ekhmaj (2015) later tested and validated this empirical model using multiple experimental datasets. To enhance its accuracy and applicability, the model was refined by incorporating the saturated soil water content as one of its parameters. This modification further improved the model's performance, making it a valuable tool for estimating water distribution patterns in surface drip irrigation systems. Kandelous and Šimůnek (2010) developed an empirical model to forecast the distances between a subsurface point source and the wetting front, considering upward, downward, and horizontal directions. Their empirical model was established through laboratory experiments, employing a subsurface dripper situated at a depth of 30 cm within clay loam soil. By analyzing the data collected from these experiments, they derived a practical and effective model that accurately estimates the extent of water movement in different directions from the subsurface source. This model proves valuable in understanding and optimizing water distribution patterns in subsurface drip irrigation systems, offering insights into the dynamics of water movement in the soil. Al-Ogaidi et al. (2016), empirical equations were developed to estimate drip emitter wetting patterns. Their proposed model demonstrated high accuracy in predicting the complete wetting pattern, and it successfully replicated experimental data published in prior studies. The empirical equations devised by Al-Ogaidi and colleagues provide a reliable tool for evaluating water distribution in drip irrigation systems, facilitating the optimization of irrigation practices and enhancing water use efficiency in agriculture. Iqbal et al. (2017) utilized a standardized sandbox model to derive empirical equations for determining the maximum wetted radius and depth. They considered a range of variables, including emitter discharge, irrigation duration, soil bulk density, hydraulic conductivity, initial and final soil moisture levels, and the percentage composition of sand, silt, and clay in the soil. Employing these parameters, the empirical equations performed effectively and demonstrated satisfactory accuracy. This approach provides valuable insights into the factors influencing water distribution in irrigation systems, enabling more precise planning and management of agricultural practices to enhance water efficiency. As indicated in the literature by Arpna Bajpai and Arun Kaushal (2020), the wetted depth, width, and volume of soil stand out as crucial characteristics in the design of drip emitters. Given that different soils possess distinct infiltration rates, it becomes imperative to study the wetting patterns generated by various emitter discharges across diverse soil types. This investigation is essential not only to conserve water but also to enhance the overall efficiency of the drip irrigation system. Furthermore, accurately determining the appropriate emitter discharge for each soil type plays a pivotal role in the development of an effective and optimized drip irrigation system. By understanding and considering these factors, farmers and practitioners can maximize water usage efficiency and achieve sustainable and productive agricultural practices.

In this research, the focus was on evaluating the precision of various statistical models used to estimate wetting zone dimensions. The study involved comparing the predictions of these models with actual field data to assess their performance. Additionally, the investigation delved into the specific advantages and limitations of each statistical model employed in this study. By doing so, a comprehensive understanding of the efficacy of these models in estimating wetness zone dimensions was obtained, enabling researchers and practitioners to make informed decisions regarding their applicability and usefulness in practical irrigation planning and management.

Material and Methods

Field experiments were conducted at Tamil Nadu Agricultural University to gather crucial data on the wetting pattern observed during surface drip irrigation. The study aimed to obtain first-hand information regarding the distribution of water in the soil under real-world conditions, contributing valuable insights into the behaviour of water movement and its impact on crop growth and water use efficiency.

Measurement of Horizontal and Vertical Water Movement

A field experiment was carried out with a drip irrigation system utilizing an inline lateral that featured an emitter spacing of 45 cm and a discharge rate of 4 litre per hour. The system was installed in the field without any crops initially. Different operational durations, including 10 min, 20 min, 30 min, 50 min, 60 min, 70 min, 80 min, 90 min, 100 min, 120 min, and 140 min, were tested. At the end of each predetermined time interval, the soil around the emitter was excavated, and the distance between the wetting front and the emitter was measured in both the horizontal and vertical downward directions. The maximum distances in these particular directions were then compared with various models to evaluate their accuracy in predicting the wetting pattern of the drip irrigation system.This study utilized the experimental data to develop various statistical models, namely Exponential, Linear, Logarithmic, Polynomial, and Power models, for predicting soil water movement. These models were carefully examined, and the best fit model was selected to estimate the wetting front advances in the inline drip irrigation system at different operation times. To evaluate the accuracy of the selected model, the horizontal and vertical water movement calculated by the statistical model was compared with the observed water movement data. This comparison allowed researchers to assess the model's performance in accurately predicting water distribution and movement in the drip irrigation system under varying operational conditions.

Soil physical properties of experimental plot

Picture 1

Wetting Pattern of Experimental Plot

Physical properties of the soil	Bulk density, g cc^{-1}	1.48
	Field capacity, %	27.6
	Permanent wilting point, %	18.6
	Infiltration rate, cm h^{-1}	1.53
	Textural class	Clay loam

	
Vertical Measurement of wetting Pattern	**Horizontal Measurement of wetting Pattern**

Table 1Vertical Measurement during wetting pattern in the field

Time (min.)	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**
Depth (cm)	11.30	12.60	15.50	17	20	20	20	20.60	21.60	21.60	23	23.90	24.60	25.30

Table 2Horizontal Measurement during wetting pattern in the field

Time (min.)	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**
Depth (cm)	19	23	24	26	30	35	32	33	36	35	36	36	35	35

Table 3

Statistical Modelings

The research focused on a line source drip irrigation system, where statistical models were employed to identify the most suitable wetting front model for different operation times. To achieve this, the study utilized Exponential, Linear, and Logarithmic, Polynomial, and Power models as the statistical methods for analysis. By exploring the performance of these models, researchers aimed to determine the best-fit approach to accurately predict the wetting front and understand how water spreads in the soil during various stages of the irrigation system's operation.

(a) Exponential Model

The exponential model rooted in the concept of degrading failure processes, was devised based on the following equation.

$$\boldsymbol{y = b\ e^{at}} \text{...eq. (1)}$$

(b) Linear Model

Linear models are mathematical tools that characterize the relationship between a continuous response variable and one or more predictor variables. By employing linear models, one can gain insights into the behaviour of intricate systems or analyse experimental data to make predictions and draw meaningful conclusions. These models serve as valuable tools in various fields, allowing researchers to explore and understand the underlying patterns and trends within their data, leading to more informed decision-making and in-depth analysis of complex phenomena.

$\boldsymbol{y = \beta_0 \; \sum \beta_i x_i + \mathcal{E}_i}$ ...eq. (2)

(c) Logarithmic Model

Logarithmic functions are mathematical functions that act as the inverses of exponential functions. In other words, they represent the opposite operations to exponential functions.

$\boldsymbol{y = log_a \, x}$...eq. (3)

(d) Polynomial model

Polynomial models serve as valuable tools for analysing how input factors influence responses and in what manner. These models enable researchers to explore the relationships between variables and identify the driving factors that affect the outcome. By utilizing polynomial models, one can gain valuable insights into the direction and magnitude of the effects of different input factors, contributing to a comprehensive understanding of complex systems and facilitating informed decision-making processes.

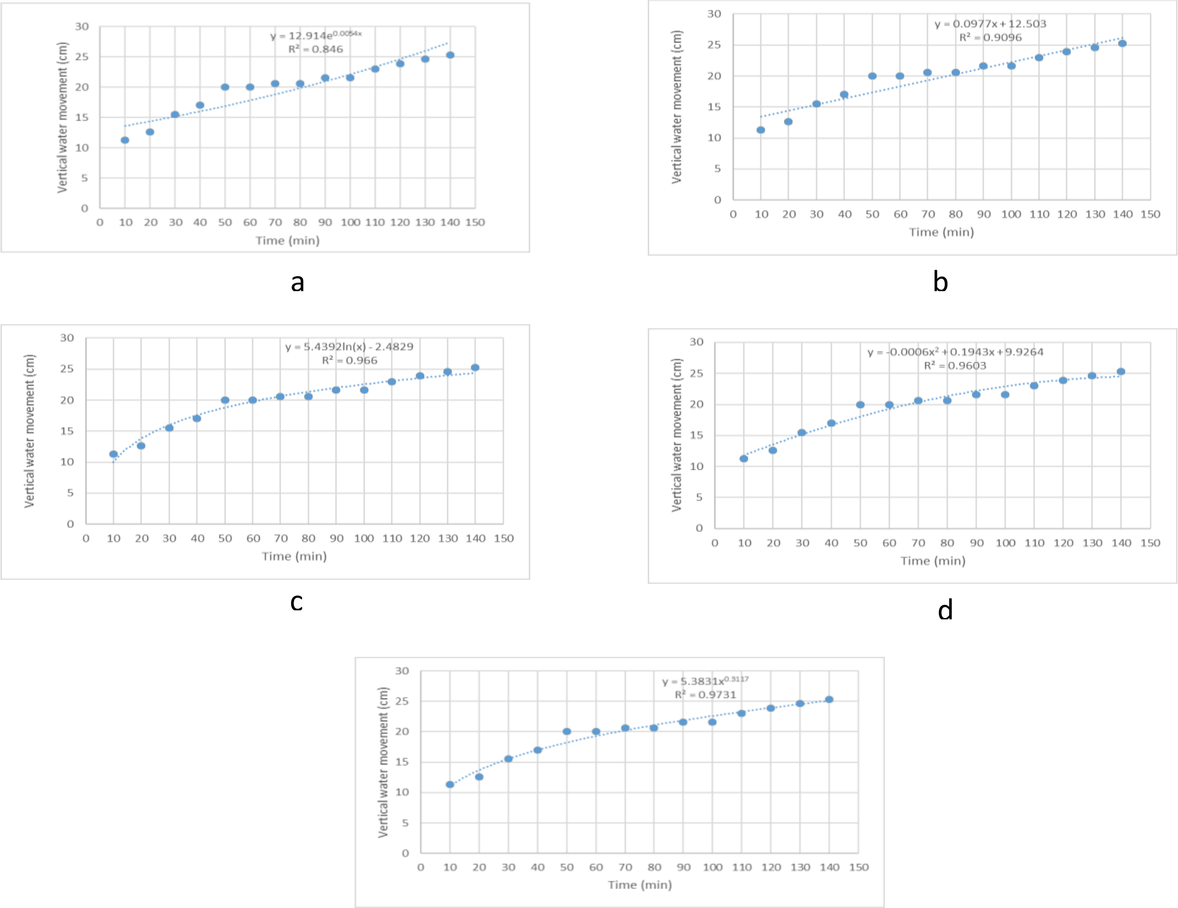
$\boldsymbol{y = a_0 + a_1 x_1 + a_2 x_2 + a_{11} x^2{}_1 + a_{22} x^2{}_2 + a_{12} x_1 x_2 + \mathcal{E}}$...eq. (4)

(e) Power Model

The power model entails taking the logarithm of both the dependent and independent variables. By conducting a bivariate regression on the transformed data, the resulting slope yields the power exponent in the model. This approach allows researchers to effectively capture the relationship between the variables and determine the power relationship between them. Utilizing the power model and regression analysis aids in uncovering the underlying patterns and associations within the data, providing valuable insights into the behaviour of the variables and their interdependencies.

$\boldsymbol{y = \; a x^n}$...eq. (5)

Graph Fig. 1forObserved Vertical water movement **a**(Exponential Model)**, b** (Linear Model)**, c** (Logarithmic Model)**, d** (Polynomial model)**, e** (Power Model)**.**



a

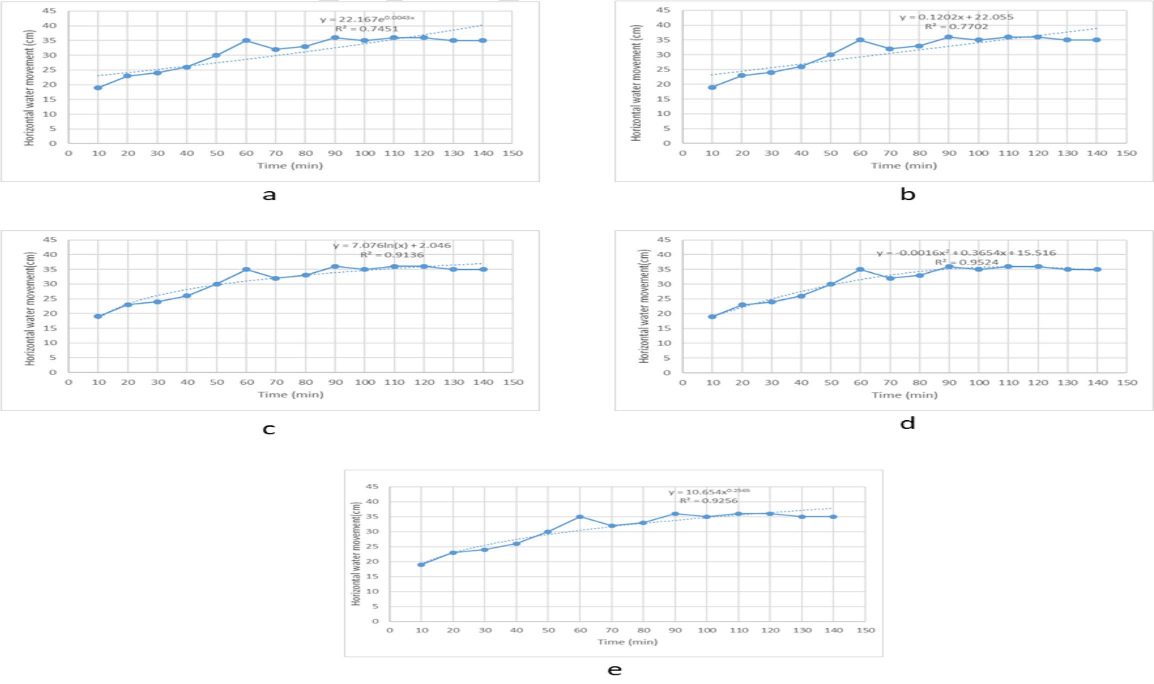
b

c

d

e

Graph Fig. 2 for Observed Horizontal water movement **a**(Exponential Model)**, b** (Linear Model)**, c** (Logarithmic Model)**,d** (Polynomial model)**, e** (Power Model)**.**



a

b

c

d

e

Performance Evaluation of Statistical Models analysis

1. **Coefficient of correlation (CC)**

The coefficient of correlation quantifies the degree of linear association between the predicted values and the target values in a given model. It serves as a valuable metric to assess how well the model's predictions align with the actual observed data, providing valuable insights into the strength and direction of the relationship between the variables.

The coefficient of correlation (CC) is calculated as follows:

$$\boldsymbol{C.C} = \frac{\boldsymbol{Z\sum ab - (\sum a)(\sum b)}}{\boldsymbol{\sqrt{Z}(\sum a^2) - ((\sum a)^2 \sqrt{Z}(\sum b^2) - ((\sum b)^2}} \quad \text{…eq. (6)}$$

The correlation coefficient ranges from -1 to +1, representing the strength and direction of the relationship between the actual and predicted data. A correlation coefficient of zero indicates that there is no linear relationship between the two sets of data, implying that they are not related or do not exhibit any systematic pattern when compared to each other.

2. **Root mean square error (RMSE)**

This approach amplifies the prediction error, which reflects the discrepancy between the predicted value and the actual value. To gauge the root mean squared error (RMSE), researchers evaluate the performance of the model by quantifying the average square difference between the predicted values and the corresponding actual values.

$$\boldsymbol{RMSE = \sqrt{\frac{1}{2}} \sum_{i=1}^{z} (a_i - b_i)^2} \text{…eq. (7)}$$

In this context, ‘a’ represents the calculated values of the infiltration rate, ‘b’ stands for the observed values of the infiltration rate, and ‘z’ denotes the total number of observations.

The concurrent utilization of Coefficient of Correlation (C.C) and Root Mean Square Error (RMSE) offers a comprehensive assessment of the performance of each model and facilitates a reliable judgment regarding the accuracy of the five modeling approaches employed in the present study. By considering these evaluation metrics together, researchers can gain a more complete understanding of how well the models capture the observed data and make informed comparisons between different modeling techniques.

Table 4Performance evaluation statistical models for the Vertical water movement

Sr. No	**Models**	**Coefficient of correlation (C.C)**	**Root mean square error (RMSE) (cm)**
1	Exponential	0.93	1.60
2	Linear	0.95	1.24
3	Logarithmic	0.98	0.76
4	Polynomial	0.98	0.92
5	Power	0.99	0.68

Table 5Performance evaluation statistical models for the Horizontal water movement

Sr. No	Models	Coefficient of correlation (C.C)	Root mean square error (RMSE) (cm)
1	Exponential	0.84	3.06
2	Linear	0.88	2.65
3	Logarithmic	0.96	1.62
4	Polynomial	0.98	1.25
5	Power	0.91	2.45

RESULTS AND DISCUSSION

In this study, the proposed statistical models for both vertical and horizontal water movement progress are presented in Tables 4 and 5, respectively. Through thorough statistical analysis, the most suitable model in each scenario was determined. The outcomes of the statistical analysis criterion are illustrated in Tables 6 and 7. As per the results, for Vertical water movement, the Logarithmic model emerged as the best fit, exhibiting C.C and RMSE values of 0.98 cm and 0.76 cm respectively. On the other hand, the Polynomial model demonstrated superior accuracy for horizontal progress, with Coefficient of Correlation (C.C) and Root Mean Square Error (RMSE) values of 0.98 cm and 1.25 cm respectively. These findings highlight the precision of the selected models in capturing the water movement patterns and emphasize their relevance in predicting both vertical and horizontal water movement in the drip irrigation system.

Table 6Statistical model Equations for Vertical water movement in clay loam soil

Sr. No	Models	Equation
1	Exponential	$y = 12.914e^{0.0054x}$
2	Linear	$y = 0.0977x + 12.503$
3	Logarithmic	$y = 5.4392\ln(x) - 2.4829$
4	Polynomial	$y = -0.0006x^2 + 0.1943x + 9.9264$
5	Power	$y = 5.3831x^{0.3117}$

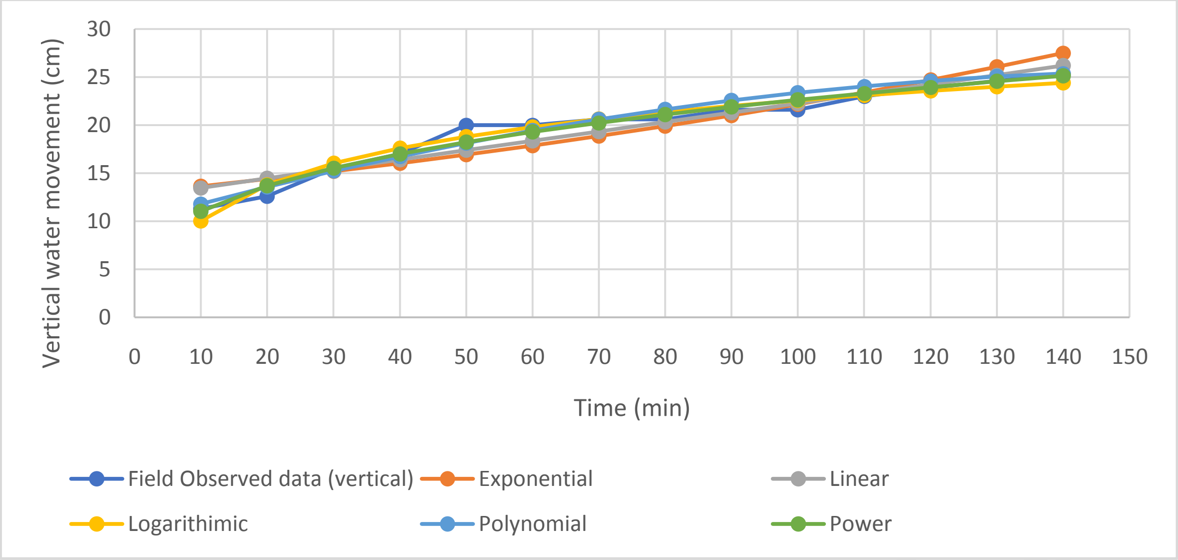
Where y = Vertical measurement (cm), x = Elapsed time (min)

Table 7 :Statistical model Equations for Horizontal water movement in clay loam soil

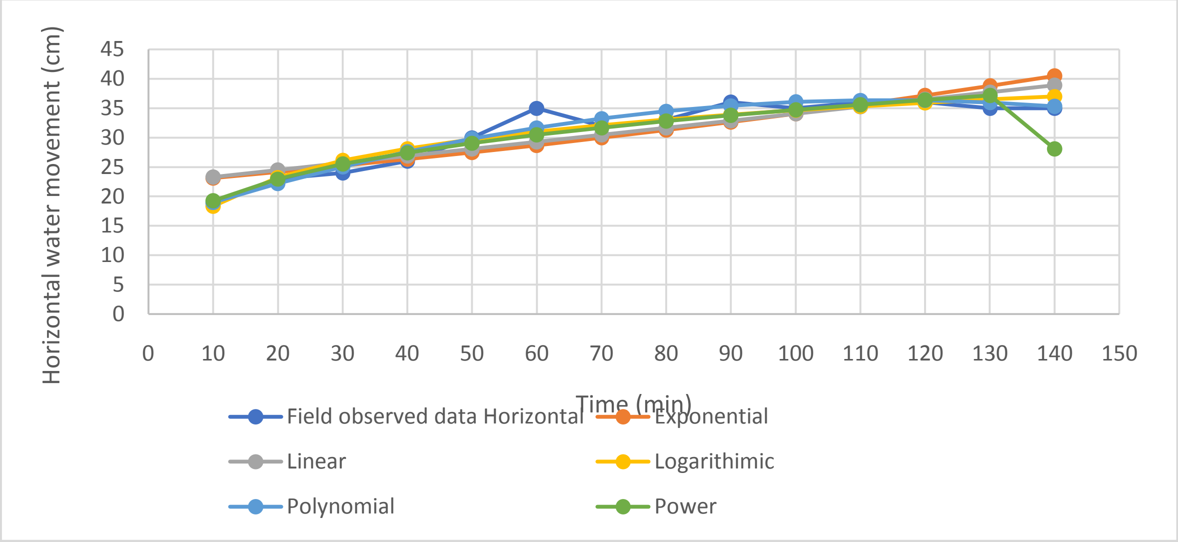
Sr. No	Models	Equation
1	Exponential	$y = 22.167e^{0.0043x}$
2	Linear	$y = 0.1202x + 22.055$
3	Logarithmic	$y = 7.076\ln(x) + 2.046$
4	Polynomial	$y = -0.0016x^2 + 0.3654x + 15.516$
5	Power	$y = 10.654x^{0.2565}$

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

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



Graph Fig. 4 Comparison of observed wetting pattern in Horizontal path with statistical models



In the clay loam soil, the vertical and horizontal water movement was meticulously observed and compared to the predictions made by the best fit statistical models. The comparison involved plotting the predicted vertical and horizontal water movement against the operating time, as depicted in Graph Fig. 3 and 4. The GraphFig. illustrate that the vertical and horizontal soil water movement, as predicted by the logarithmic and polynomial models at various operation times, closely follows the same pattern as the observed vertical and horizontal soil water movement.Kyada and Munjarappa (2013) conducted a research on clay loam soil, similar findings were reported. They observed that the wetted width experienced a rapid increase at the initial stages of irrigation but demonstrated a considerably slower rate of increase as the irrigation process progressed.Likewise, in a study conducted by Salwa et al. (2010), they found similar results concerning the wetting front in different soil types. In sandy soil, the vertical wetting front was notably larger compared to clayey soil, approximately 36.07% more. Conversely, the horizontal wetting front was greater in clayey soil, approximately 13.08% more compared to sandy soil. The researchers also observed that in clayey soils, higher emitter discharge rates promoted both vertical and lateral water movement in the context of drip irrigation. At higher flow rates, soil moisture content was higher, whereas at lower discharge rates, soil moisture content was lower. In such conditions, lower discharge rates resulted in larger wetted radii. Additionally, after irrigation, the redistribution of water was nearly doubled in depth, but the width of the moist soil did not show significant enlargement.Arpna and Arun also conducted a comprehensive review on water distribution under trickle irrigation, where they discussed and reported numerous similar findings. Their review highlighted various outcomes that mirrored the observations made in other studies concerning water movement and wetting patterns in different soil types under drip irrigation.

As the wetting front reaches the soil surface, the downward water circulation intensifies under natural field conditions. However, statistical methods like logarithmic and polynomial models often overlook this phenomenon and estimate the water movement in each direction (Vertical and horizontal) independently. Consequently, the observed downhill water movement was considerably faster than what the statistical models predicted. To address this discrepancy, it becomes essential to enhance the current boundary condition of drip tubing. This improvement should consider situations where constant water flux is specified during irrigation for soils with low hydraulic conductivity, fine-textured soils, or simulations involving high water application rates. Notably, in soils with low permeability, the saturation caused by irrigation can lead to significant positive pressure around the drip tape. In response to this pressure build-up, the water flux should decrease instead of remaining constant to accurately model the behaviour of water movement.

Conclusion

In this study, the predictions of Vertical soil water content distributions using a logarithmic model closely align with the experimental data and horizontal soil water content distributions using a polynomial model. These results indicate that employing a logarithmic model for vertical water flow and a polynomial model for horizontal water flow can serve as effective tools for investigating and devising drip irrigation management strategies. The accuracy and agreement between the model predictions and experimental data suggest that such modeling approaches can significantly contribute to the research and planning of efficient drip irrigation practices.The experimental findings lead to the conclusion that an increase in irrigation volume results in a corresponding increase in both vertical and horizontal water movement. Furthermore, the suggested statistical models can be utilized to simulate the maximum vertical and horizontal water movement under varying conditions of irrigation volume, providing valuable insights into the behaviour of water distribution in the system.The results obtained from the statistical models exhibit satisfactory accuracy, instilling confidence in their reliability. It is essential to note that these models rely on data and are specifically applicable to soils that bear similarities to the ones used for developing the equations. By employing the established model, one can effectively determine the appropriate emitter spacing, leading to reduced costs associated with drip laterals. This approach contributes to more efficient irrigation design and resource utilization.

References

1. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.; Fetzer, I.; Bennett, E.; Biggs, R.; Carpenter, S. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *348*, 1217.

2. FAO. Scheme Water Management. Rome, Italy. 2023. Available online: **https://www.fao.org/land-water/water/water-management/zh/** (accessed on 14 February 2023).

3. Siyal, A.A.; Bristow, K.L.; Šimůnek, J. Minimizing nitrogen leaching from furrow irrigation through novel fertilizer placement and soil surface management strategies. *Agric. Water Manag.* **2012**, *115*, 242–251.

4. Bajpai, A.; Kaushal, A. Soil moisture distribution under trickle irrigation: A review. *Water Supply* **2020**, *20*, 761–772.

5. Moursy, M.A.M.; ElFetyany, M.; Meleha, A.M.I.; El-Bialy, M.A. Productivity and profitability of modern irrigation methods through the application of on-farm drip irrigation on some crops in the Northern Nile Delta of Egypt. *Alex. Eng. J.* **2023**, *62*, 349–356.

6. Flores, J.H.N.; Faria, L.C.; Neto, O.R.; Diotto, A.V.; Colombo, A. Methodology for determining the emitter local head loss in drip irrigation systems. *J. Irrig. Drain. Eng.* **2021**, *147*, 06020014.

7. Fukai, S.; Mitchell, J. Factors determining water use efficiency in aerobic rice. *Crop. Environ.* **2022**, *1*, 24–40.

8. Gebremeskel, G.; Gebremicael, T.G.; Hagos, H.; Gebremedhin, T.; Kifle, M. Farmers' perception towards the challenges and determinant factors in the adoption of drip irrigation in the semi-arid areas of Tigray, Ethiopia. Sustain. *Water Resour. Manag.* **2018**, *4*, 527–537.

9. Zakhem, B.A.; Al Ain, F.; Hafez, R. Assessment of field water budget components for increasing water productivity under drip irrigation in arid and semi-arid areas, Syria. *Irrig. Drain.* **2019**, *68*, 452–463.

10. Pourgholam-Amiji, M.; Liaghat, A.; Khoshravesh, M.; Azamathulla, H.M. Improving rice water productivity using alternative irrigation (case study: North of Iran). *Water Supply* **2020**, *21*, 1216–1227.

11. Bansal, G.; Mahajan, A.; Verma, A.; Singh, D.B. A review on materialistic approach to drip irrigation system. *Mater. Today: Proc.* **2021**, *46*, 10712–10717.

12. Karimi, B., Karimi, N., Shiri, J. et al. Modeling moisture redistribution of drip irrigation systems by soil and system parameters: regression-based approaches. Stoch Environ Res Risk Assess **2022,** 36, 157–172.

13. Bakhtiar Karimi, Parva Mohammadi, Hadi Sanikhani, SinanQ. Salih, Zaher Mundher Yaseen. 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, November **2020**, 105767.

14. Ghumman, A. R., Iqbal, M., Ahmed, S. & Hashmi, H. N.; Experimental and numerical investigations for optimal emitter spacing in drip irrigation. Irrigation and Drainage, **2018**, 67(5), 724–737. https://doi.org/10.1002/ird.2284.

15. Schwartzman, B. M. & Zur, B.; Emitter Spac-ing and Geometry of Wetted Soil Volume. Journal of Irri-gation and Drainage Engineering, **1987**, 112(3), 242–253.

16. Amin, M. S. M. &Ekhmaj, A.; Drip Irrigation Water Distribution Pattern Calculator. i(July 2006), **2015**, 503–513.

17. Kandelous, M. M. & Šimůnek, J.; Comparison of numerical, analytical, and empirical models to estimate wetting patterns for surface and subsurface drip irrigation. Irrigation Science, **2010**, 28(5), 435–444. https://doi.org/10.1007/s00271-009-0205-9.

18. Al-Ogaidi, A. A. M., Wayayok, A., Rowshon, M. K. & Ab-dullah, A. F.; Wetting patterns estimation under drip irrigation systems using an enhanced empirical mod-el. Agricultural Water Management, **2016**, 176, 203–213. https://doi.org/10.1016/j.agwat.2016.06.002.

19. Iqbal, M., Ghumman, A. R. & Hashmi, H. N.; Study of wetting pattern under drip–emitter using sand box mod-el and empirical equations. Pakistan Journal of Agricultur-al Sciences, **2017**, 54(3), 699–709. https://doi.org/10.21162/PAKJAS/17.6086.

20. Arpna Bajpai & Arun Kaushal; Soil moisture distri-bution under trickle irrigation. Water Supply. **2020**, 761–772. https://doi.org/10.2166/ws.2020.005.

21. Kyada, K. M. &Munjarappa, B. J; Study on pres-suredischarge relationship and wetting pattern under drip irrigation system. International Journal of Nature Science, **2013**, 4 (2), 274–283.

22. Salwa, H. A., Hegazi, M. M., Gindy, A. G. M. E. & Claudia, S.; Performance of ultra-low rate of trickle irriga-tion. Journal of Agricultural Engineering, **2010**, 27 (2), 549–564.