Simulation and analysis of drip irrigation infiltration

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ABSTRACT

Sufficient water supply is a major factor for crop growth and production. Management and controls of irrigation are keys to achieve farm profitability as well as high water use efficiency especially in the arid and semi-arid areas where high profit upland crops are grown. In many irrigation methods, drip irrigation is popular for upland irrigation because water can be irrigated effectively to the root zone of the crop. The related unsaturated flow problem has drawn much attention because of the complex relations among the unsaturated hydraulic conductivity, piezometric head and moisture content in recent years. It is obvious that direct simulation of unsaturated flow using 3-dimensional numerical model requires huge memory and consuming time. In order to simulate the unsaturated flow problem from drip irrigation infiltration, an axial symmetric unsaturated flow model was presented to reduce the computation time and required memory. The objectives of this research are to establish an axial-symmetric unsaturated flow model and to analyze the flow pattern of various types of soils.

Keywords: *unsaturated flow; drip irrigation*

1. INTRODUCTION

Drip irrigation and sprinkle irrigation are frequently used to reach the maximum water use efficiency in arid and semi-arid areas (Hamouri *et al.*, 1996; Tarjueo *et al.*, 1999; and Fabeiro *et al.*, 2002). Sufficient water supply is usually considered as one of the major factors of crop production. As water resources demands are increasing in recently years, the water use efficiency is getting more and more important. In many irrigation methods, drip irrigation is popular for upland crops because the irrigated water can reach the root zone of the crop directly. However, if the irrigated water is not enough, crop production can be reduced. On the other hand, it is waste of water. Hence, understanding soil water movement is helpful in drip irrigation design.

Drip irrigation is often used for high efficient crop in Taiwan as well as in many other places. The economic feasibility of drip irrigation was carefully evaluated (Tiwari *et al.*, 1998). Application of drip irrigation was found to increase in yields compared to that of furrow irrigation. As measurement of drip irrigation water flow is easier than other irrigation methods, this irrigation method is used to evaluate crop evapotranspiration and crop coefficient for various plants such as eggplant and sweet lime (Chartzoulakis and Drosos, 1995 ; Sepaskhah and Kashefipour, 1995). The wetting pattern of drip irrigation was studied using neutron moisture meter and the results can be applied to drip irrigation design (Vidhana Arachchi, 1998). It can be concluded from the literature review that drip irrigation was popular for a water supply method in most arid and semi-arid areas. It is interesting to visualize the soil water distribution from a dripper to obtain useful information in designing drip flow rate and dripping time. However, *in situ* measurement of soil moisture content is feasible but time consuming and expensive. A numerical model is an easier way of obtaining information of water movement in the soil. Thanks to the development and research of modeling unsaturated flow problems. The unsaturated flow problems have been extensively studied for the complex relations among the unsaturated hydraulic conductivity, piezometric head and moisture content. Because direct unsaturated flow simulation using 3-dimensional numerical model requires huge computer memory and computation time, an axial symmetric unsaturated flow model was developed in this study to simulate the 3-dimensional problem. The axial symmetric unsaturated flow model is efficient in computation and memory because it implements computations by 2-dimensional method to obtain the 3-dimensional results. The objective of this research is to develop a numerical model for simulating drip irrigation infiltration. Because water movement phenomena is different in various soils, drip irrigation water move in five types of soils including a soil sample *in situ* were analyzed by using the numerical model in this research.

2. CONCEPTUAL MODEL

Figure 1 illustrates the conceptual model of soil water movement from a dripper. The irrigated water can be visualized as a "point" source which injecting to the ground surface. The injected water flows vertically and horizontally into the soil. The soil moisture content near the source is greater than that away from the source conceptually. The moisture content contour's shapes are axial symmetric bulbs. Hence, the axial symmetric flow pattern can be modeled to present a 3-dimensional problem.

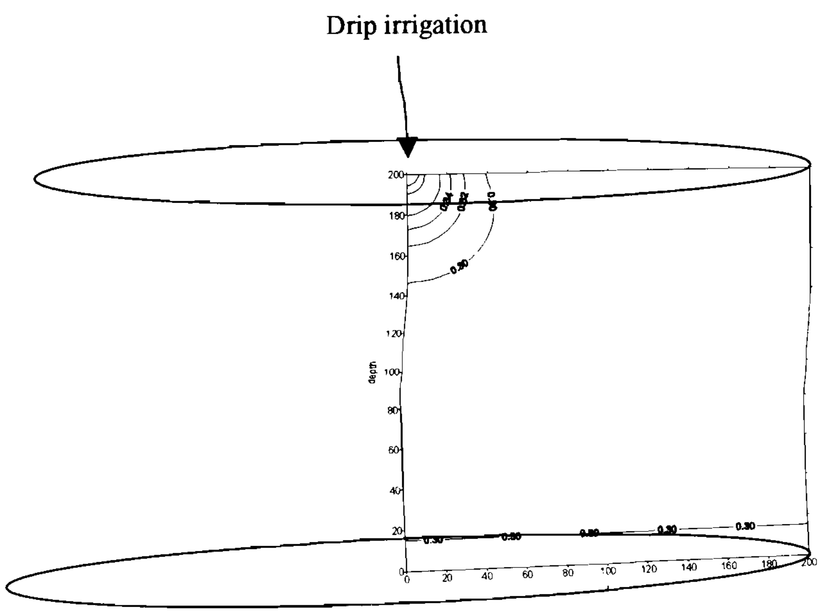

Figure 1. The conceptual model of soil water flow of drip irrigation.

3. GOVERNING EQUATION

3.1 Introduction

The infiltration problem of unsaturated flow has drawn much attention for its importance in approximating groundwater recharge (Parlange *et al.*, 1985; Allison *et al.*, 1994; and Nimmo *et al.*, 1994). The mathematical unsaturated flow model was developed by Richards in 1931. However, the non-linear relation among soil moisture content, piezometric and unsaturated hydraulic conductivity was not well defined until van Genuchten's function (van Genuchten, 1980). This function has been widely used for many analysis.

3.2 Richards equation and van Genuchten's function

The unsaturated flow is mostly described by Richards equation:

$$F\frac{\partial h}{\partial t} = \nabla \cdot \left[K_r \underline{\underline{K_s}} \cdot (\nabla h + \nabla z)\right] + q' \tag{1}$$

where $F = \alpha'\frac{\theta}{n_e} + \beta'\theta + \frac{d\theta}{dh}$ =water capacity, h =pressure head, z = potential head, $\underline{\underline{K_r}}$ =relative hydraulic conductivity, $\underline{\underline{K_s}}$ =saturated hydraulic conductivity tensor, t=time, q' =internal source/sink, n_e=effective porosity, θ =moisture content, α'=modified compressibility of soil, and β' =modified compressibility of water. In unsaturated flow, the effective hydraulic conductivity ($\underline{\underline{K}}$) is a function of pressure head, the relationship between the effective hydraulic and the saturated hydraulic conductivity ($\underline{\underline{K_s}}$) is

$$\underline{\underline{K}} = K_r \underline{\underline{K_s}} \tag{2}$$

The relation between of K_r and effective moisture content (θ_e) can be expressed by van Genuchten functions (van Genuchten, 1980)

$$K_r = \theta_e^{0.5}\left[1-\left(1-\theta_e^{1/\gamma}\right)^{\gamma}\right]^2 \tag{3}$$

when

$$h < 0, \ \theta_e = \left[1+\left(|\alpha h|\right)^{\beta}\right]^{-\gamma} \tag{4}$$

when

$$h \geq 0, \ \theta_e = 1 \tag{5}$$

and

$$\theta_w = \theta_r + \theta_e(\theta_s - \theta_r) \tag{6}$$

$$\gamma = 1 - \frac{1}{\beta} \tag{7}$$

where θ_w = moisture content, θ_s = saturation moisture content, θ_r =residual moisture content, β, γ : soil-specific exponents, α : soil-specific coefficient.

3.3 Domain transform

It can be seen that numerical simulation of Equation (1) is time consuming and requires huge memory. *In order to reduce the computation time and memory, Richards equation was* transformed to the cylindrical coordinate according to the conceptual model. The 3-dimensional flow problem *in the* rectangular *coordinates (x, y, z) can be simulated by 2-*dimensional method in the cylindrical coordinates (r, θ , z) since the flow pattern is symmetric to the axis z. The ∇ – operator in the cylindrical coordinates can be obtained by

$$\nabla = \underline{\delta}_r \frac{\partial}{\partial r} + \underline{\delta}_\theta \frac{1}{r}\frac{\partial}{\partial \theta} + \underline{\delta}_z \frac{\partial}{\partial z} \tag{8}$$

where $\underline{\delta}_r$, $\underline{\delta}_\theta$ and $\underline{\delta}_z$ are unit vectors of cylindrical coordinates (Bird *et al.*, 1987). Finite element method is used to solve the transformed Richards equation. Index method and conjugate-gradient-like methods (Tsay and Ju, 1998) were applied to store and solve matrices.

4. SOIL SAMPLING AND PROPERTIES

Simulation of the drip irrigation flow pattern was applied to a pineapple farm in Long-Tian district, Taidong, Taiwan to exam the designed irrigation flow rate (Figure 2). The area of the selected pineapple farm is 79 meters long and 23 meters wide. Five soil samples from the *field were obtained to approximate the parameters in equations (4) and (6) by soil tests. The* relations between pressure head and moisture content of the samples is shown in Figure 3. It is approximated from the figure that θ_r =0, θ_s =0.42, α =0.00976, β =1.29, and Ks = 10^{-2} cm/sec.

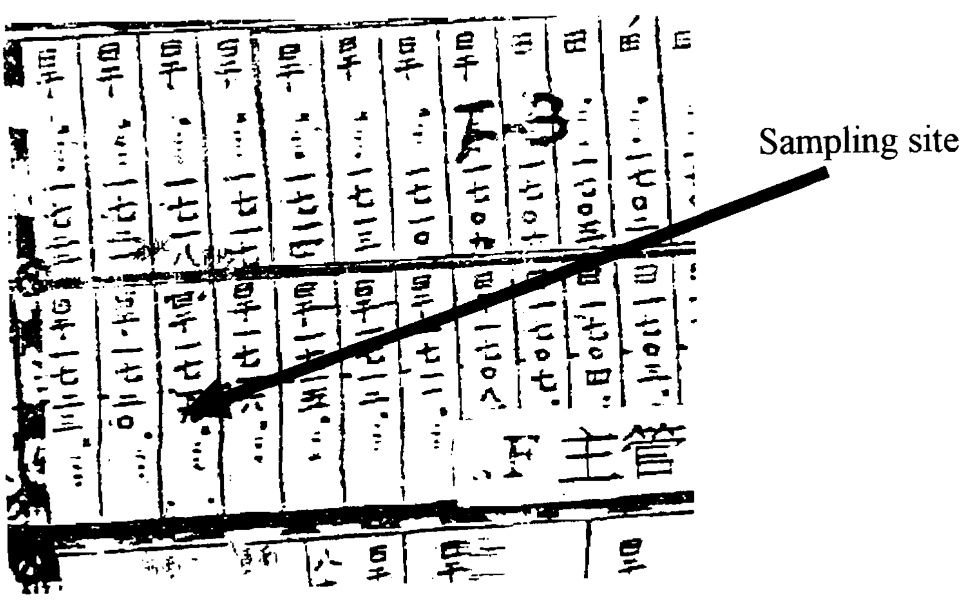

Figure 2. Soil sampling site in Long-Tian district, Taidong, Taiwan.

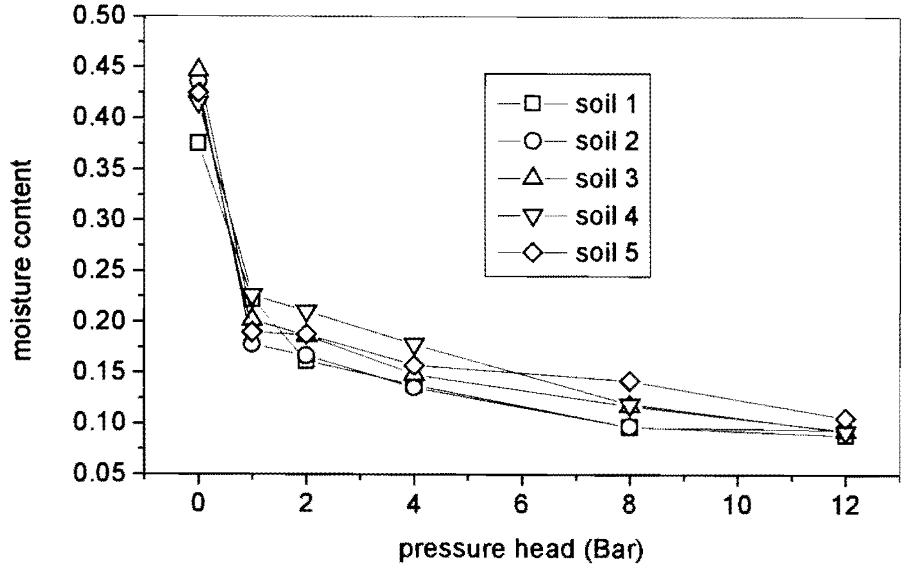

Figure 3. Relations between soil suction and moisture content of five soil samples in the selected pineapple farm.

5. SIMULATION RESULTS

5.1 Assumptions

The numerical simulation of flow pattern due to drip irrigation assumes:
1. the soil is homogeneous and isotropic;
2. van Genuchten function is valid for estimating the nonlinear relations between soil pressure, moisture content and unsaturated hydraulic conductivity;
3. the irrigated water is infiltrated to an area with the radius of 5 cm;
4. no ponding happens during irrigation; and
5. pineapple root effect of water movement is neglected.

5.2 Flow simulation of various soils

In order to understand the flow pattern of drip irrigation, four types of soils were used. The coefficients of the soils were suggested by Femwater (Lin, *et al.*, 2000) shown in Table 1.

Table 1. Four types of Soil coefficients suggested by Femwater (Lin, *et al.*, 2000)

Soil type	θ_r	θ_s	α	β	Ks
Clay(60%)	0.121	0.38	0.0077	1.113	10^{-6} cm/sec
Loam	0.0778	0.43	0.036	1.56	10^{-4}cm/sec
Silt Loam	0.067	0.45	0.02	1.41	10^{-3} cm/sec
Sandy Loam	0.065	0.41	0.075	1.89	10^{-2} cm/sec

Figure 4 to Figure 7 indicate the infiltration of a very small irrigation rate (0.8×10^{-6} cm/sec) from the top of the ground surface for four types of soils. Flow in clay(60%) soil reach saturation more easily than other types of soils under the same conditions because clay(60%)

soil's volume porosity is much smaller than other types of soils (Figure 4).

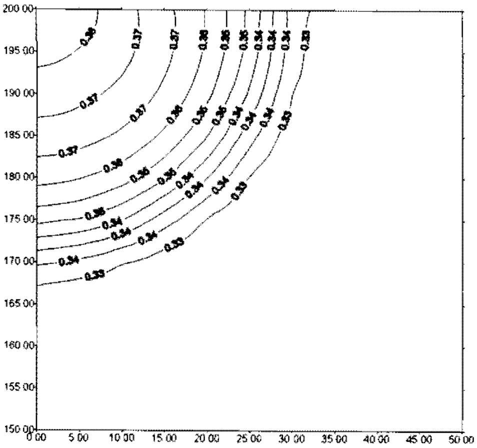

Figure 4. Infiltration of clay(60%).

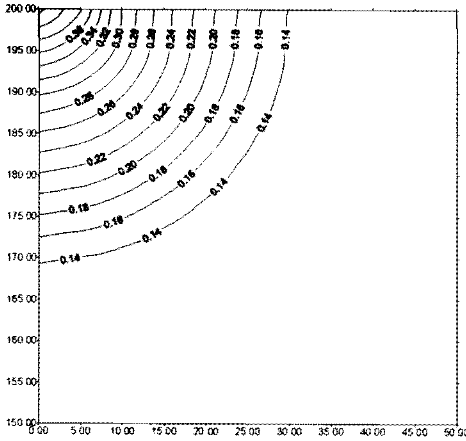

Figure 5. Infiltration of loam.

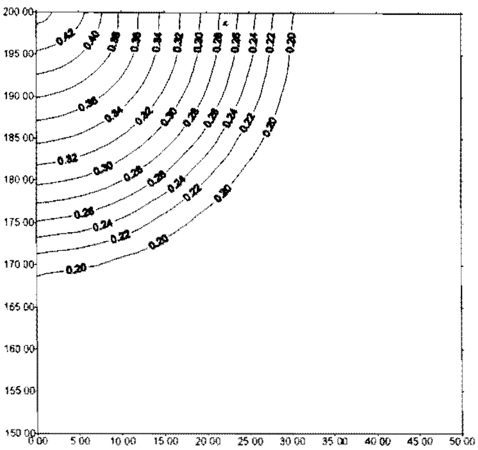

Figure 6. Infiltration of silt loam.

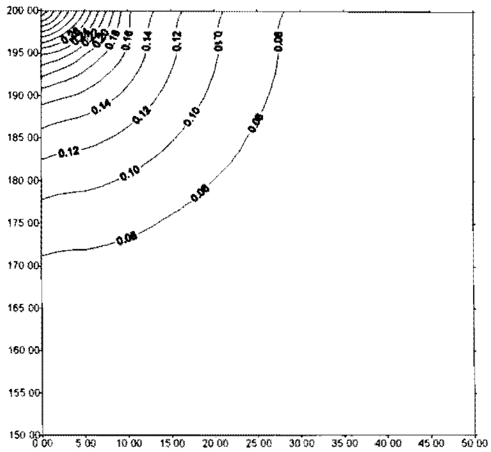

Figure 7. Infiltration of sandy loam.

5.3 Infiltration simulation *in situ*

According to the conditions of the pineapple farm *in situ* and the above assumptions, the initial result of the simulation appears to be reasonable. Figure 8 shows that when water is dripped from the left upper corner for a period of time, the moisture content contour's value is getting larger near the irrigation source.

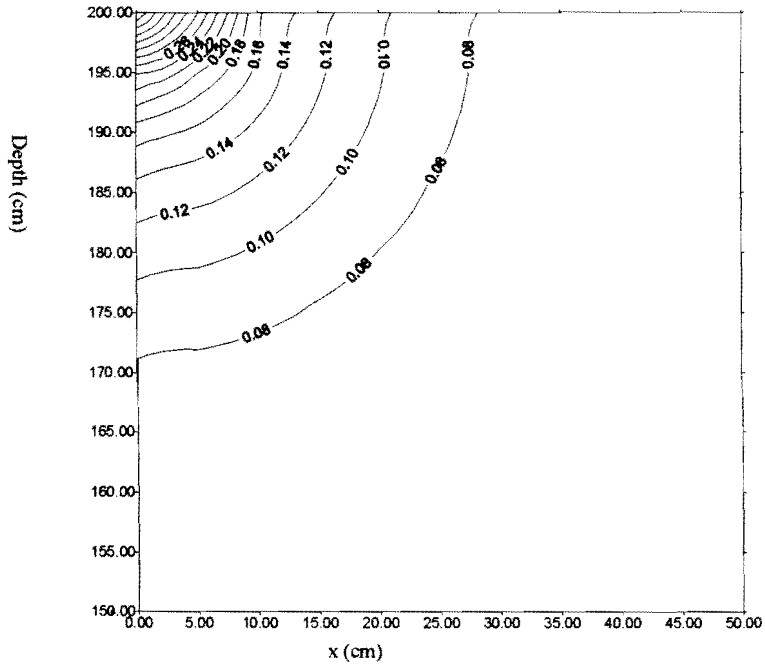

Figure 8. The moisture content contour of drip irrigation after 3,000 second when the irrigation strength is 0.8×10^{-6}cm/sec.

Figure 9 indicates that higher initial moisture content is better for water flow. The moisture content contour of 0.3 reaches 29 cm depth after 5 hours of irrigation at irrigation flow rate of 0.01768 cm/sec for a barely dry soil when the initial moisture content is 0.21. Using the same irrigation time and flow rate, the moisture content contour of 0.3 reaches 34 cm depth when the initial moisture content is 0.25.

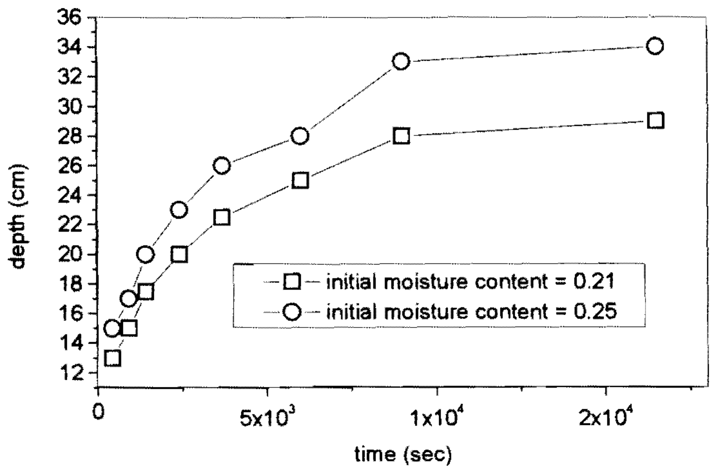

Figure 9. Relations of irrigation time and the moving depth when moisture content reaches 0.3

6. CONCLUSIONS AND DISCUSSIONS

Abundant water supply is very important to crop growth. As drip irrigation can be irrigated directly to crop root zone, it is a popular irrigation method in arid and semi-arid area. It can be concluded from this study that:

1. the soil of the pineapple farm is very close to sandy loam;
2. irrigation intervals between each irrigation schedule should be close enough since over dry soil is not good for water conveyance;
3. according to the infiltration phenomena from drip irrigation, the axial symmetric unsaturated flow model can reduce the required computation memory and time of a three dimensional model;
4. the simulated flow pattern of the pineapple farm using the axial symmetric unsaturated flow model showed reasonable results; and
5. the uniformity analysis could be modified by restricting the irrigation domain to the most effected boundary in order to get more significant comparing results.

The future work of this research suggests sand tank experiment to verify the axial symmetric unsaturated flow model.

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REFERENCES

1. Allison, G. B.; Gee, G. W. and Tyler, S. W. (1994) Vadose-zone techniques for estimating groundwater recharge in arid and semiarid regions. *Soil Sci. Soc. Am. J.*, 58, 6-14.
2. Bird, R.B.; Armstrong, R.C. and Hassager, O. (1987) *Dynamics of Polymeric Liquids*, John Wiley & Sons, New York.
3. Chartzoulakis, K. and Drosos, N. (1995) Water use and yield of greenhouse grown eggplant under drip irrigation. *Agricultural Water Management*, 28, 113-120.
4. Fabeiro, C.; de Santa Olalla, F. Martin and de Juan, J.A. (2002) Production of muskmelon (Cucumis mela L.) under controlled deficit irrigation in a semi-arid climate. *Agricultural Watèr Management*, 54, 93-105.
5. Hamouri, B.E.; Handouf, A.; Mekrane, M. Touzani, M.; Khana, A.; Khallayoune, K. and Benchokroun, T. (1996) Use of wastewater for crop production under arid and saline conditions: yield and hygienic quality of the crop and soil conditions. *Wat. Sci. Tech.*, 33(10-11), 327-334.
6. Lin, H-C J.; Richards, D. R.; Talbot, C. A.; Yeh, G-T; Cheng, J-R; Cheng, H-P; Jones, N. L. (2000) *A three-dimensional finite element computer model for simulating density-dependent flow and transport in variably saturated media Version 3.0* The department of defense, Groundwater modeling system.
7. Nimmo, J. R.; Stonestrom, D. A. and Akstin, K. C. (1994) The feasibility of recharge rate determinations using the steady-state centrifuge method. *Soil Sci. Soc. Am. J.*, 58, 49-56.
8. Parlange, J.-Y.; Haverkamp, R. and Touma, J.: Infiltration under ponded conditions (1985) 1. Optimal analytical solution and comparison with experimental observations. *Soil Sci. Soc. Am. J.*, 139, 305-311.
9. Richards, L. A. (1931) Capillary conduction of liquids through porous mediums. *physics*, 1, 318-333.
10. Sepaskhah, A.R. and Kashefipour, S.M. (1995) Evapotranspiration and crop coefficient of sweet lime under drip irrigation. *Agricultural Water Management*, 27, 331-340.
11. Tarjuelo, J.M.; Montero, J.; Honrubia, F.T.; Ortiz, J.J. and Ortega, J.F. (1999) Analysis of uniformity of sprinkle irrigation in a semi-arid area. *Agricultural Water Management*, 40, 315-331.
12. Tiwari, K.N.; Mal, P.K.; Singh, R.M. and Chattopadhyay, A. (1998) Response of okra to drip irrigation under mulch and non-mulch conditions. *Agricultural Water Management*, 38, 91-102.
13. Tsay, T.S. and Ju, S.-H. (1998) Application of a general index method to finite difference in the curvilinear coordinate. *Journal of Chinese Agricultural Engineering*, 44(4).
14. van Genuchten, M. Th. (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.*, 44, pp. 892-898.
15. Vidhana Arachchi, L.P. (1998) Preliminary requirement to design a suitable drip irrigation system for coconut in gravelly soils. *Agricultural Water Management*, 38, 169-180.