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# Experimental and Numerical Analysis of Drip Tape Layout for Irrigation of Sugarcane in Latosol

Kai Huang[1,2,*], Desuo Cai[1], Jinchuang Guo[2] and Wei Pan[2]

*[1]College of Civil Engineering and Architecture, Guangxi University, Nanning 530004, China; [2]Guangxi Institute of Hydraulic Research, Nanning 530023, China*

**Abstract:** A laboratory soil column experiment was first conducted to analyze water movement in latosol of sugarcane field under drip irrigation from single-point source at different emitter discharge rates. Next, a mathematical model of soil water movement under drip irrigation from single-point source was built using Hydrus-3D, which could accurately simulate the shape of the wetted soil volume and the distribution of volumetric water content in the experiment. Further, a Hydrus-3D model of soil water movement under drip irrigation from double-point source was built and then used to analyze the effects of critical parameters on irrigation uniformity. Results showed that emitter spacing affected irrigation uniformity greatly, but emitter discharge rate did not. According to the irrigation uniformity, project cost and operational management patterns, appropriate drip tape parameters for irrigation of sugarcane in latosol were determined: emitter discharge rate 1.38 L/h, emitter spacing 30 cm, and single-emitter irrigation volume 9.0 L.

**Keywords:** Drip tape, hydrus-3D, latosol, sugarcane field.



## 1. INTRODUCTION

Drip irrigation is a water-saving irrigation technique that uses emitters to directly deliver water or a mixture of water and fertilizer to the crop roots in a uniform and accurate way [1, 2]. The benefit of drip irrigation and the efficiency of water use are directly affected by the characteristics of the wetted soil volume, while the wetted soil volume is controlled by a variety of factors such as soil type, initial soil water content, emitter discharge rate, emitter spacing and irrigation volume [3, 4]. Thus far, relevant experimental [5-7] and numerical studies [8-10] have been conducted extensively, which provide important references for appropriate design of drip irrigation systems.

Latosol is one of the major soil types in sugarcane fields of Guangxi Province and widely occurs in the coastal areas of southern Guangxi, China. No studies have investigated the selection of drip tape layout parameters for appropriate irrigation of sugarcane in latosol. This situation leads to some degree of arbitrariness in the design of drip irrigation systems and negatively affects the benefits of drip irrigation project in Guangxi. Therefore, to find out the effects of drip tape layout parameters on the wetted soil volume in latosol under sugarcane has great implications for the design of sugarcane irrigation project in the vast regions of Guangxi.

In this study, a representative soil was selected to perform soil column experiment of drip irrigation from single-point source. Soil water movement was analyzed under drip irrigation at three emitter discharge rates according to the emitter discharge levels in common use. A mathematical model of soil water movement under drip irrigation from double-point source was built using Hydrus-3D and then used to systematically analyze the effects of critical parameters on water distribution uniformity of the wetted soil volume. Appropriate emitter spacing and discharge rate of drip tapes were selected for irrigation of sugarcane in latosol. Further, preferred irrigation volume and time were determined for drip irrigation of sugarcane at different growth stages in accordance with the patterns of sugarcane cropping, root distribution and project management.

## 2. MATERIAL AND METHODS

### 2.1. Experimental Soil

The experimental soil was collected from a sugarcane field in the pilot demonstration base for efficient water-saving irrigation technology in Wulangjiang Village of Xichang Town in Hepu County, southwestern Guangxi Province, China. Eight tons of soil was taken from the plow layer of 10–40 cm. The soil was air-dried, crushed and passed through a 2-mm sieve before use. When preparing for the experiment, the soil was loaded into boxes by layers (5-cm thick each) and compacted with a flat plate to ensure the uniformity. The contact surface between layers was roughened to prevent stratification. The initial volumetric soil water content and dry density were measured immediately after the soil was filled into the boxes. The physical properties of the test soil were shown in Table **1**.

### 2.2. Experimental Device

The experimental system was comprised of a water supply, a soil box and a soil-water monitor. The water supply

*Address correspondence to this author at the Guangxi University, Nanning 530004, China; Tel: +86-771 2185896; Fax: +86-771 2185010;
E-mail: gxhuangkai@126.com

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**Table 1. Physical properties of experimental soil.**

| Soil Classification | Mechanical Composition/% | | | Water Content/($cm^3 \cdot cm^{-3}$) | Dry Density/ ($g \cdot cm^{-3}$) |
|---|---|---|---|---|---|
| | <0.002 mm | 0.002–0.05 mm | >0.05 mm | | |
| Latosol | 1.9 | 40.5 | 57.6 | 0.065 | 1.53 |

was a peristaltic pumpcapable of adjusting the flow rate to simulate different emitter discharge rates. The soil box was a rectangular plexiglass box (100 cm long × 60 cm wide × 85 cm high). An emitter was fixed to the middle of the long side of the glass box and kept 2 cm away from the glass wall to avoid the impact of wall. Four probes of an AZS-2 soil water sensor were buried at different depths (5, 15, 25 and 35 cm, respectively), with 15 cm horizontal distance from the emitter. Data were recorded by the probes every 10 min.

When preparing for the experiment, the soil was loaded into boxes by layers (5-cm thick each) and compacted with a flat plate to ensure the uniformity. The contact surface between layers was roughened to prevent stratification.

### 2.3. Experimental Design

A laboratory soil column experiment of water movement under surface drip irrigation was conducted in common scenarios of emitter discharge rate (1.38, 2.20 and 2.80 L/h). The irrigation volume was set to 18 L. Each experiment was repeated three times and the results were expressed as the mean values. During the experiment, the soil surface was covered with a plastic film to prevent evaporation. Data were recorded every 30 min, including the surface ponding radius, the wetted surface radius and the vertical wetted depth. At the end of irrigation, soil samples were taken at 5-cm intervals by mesh-stratified sampling and used drying method for measuring soil moisture.

## 3. NUMERICAL MODEL BUILDING

### 3.1. Principle

It is assumed that the soil is an isotropic and homogeneous medium. Then soil water movement can be described using Richard's equation as follows:

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K(h)\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right]+\frac{\partial K(h)}{\partial z} \tag{1}$$

Where $\theta$ is volumetric soil water content ($cm^3/cm^3$) ; $h$ is negative hydraulic head (cm); $t$ is time (min); and $K(h)$ is unsaturated hydraulic conductivity (cm/min).

The parameters of soil water movement were determined using pedo-transfer functions [11]. The van Genuchten model was used to describe Hydrus-3D as follows:

$$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta_s-\theta_r}{[1+|\alpha h|^n]^m}, h<0\\ \theta_s, h\geq 0\end{cases} \tag{2}$$

$$K(h)=\begin{cases}K_s S_e^l[1-(1-S_e^{1/m})^m]^2, h<0\\ K_s, h\geq 0\end{cases} \tag{3}$$

in which

$$S_e=\frac{\theta-\theta_r}{\theta_s-\theta_r} \tag{4}$$

$$m=1-1/n,\ n>1 \tag{5}$$

where $S_e$ is effective soil water saturation ($cm^3/cm^3$); $\theta_s$ is saturated water content ($cm^3/cm^3$); $\theta_r$ is residual water content ($cm^3/cm^3$); $K_s$ is saturated hydraulic conductivity (cm/min); $l$ is pore connectivity factor ($l$ = 0.5); $m$ and $n$ are shape factors; and $\alpha$ is air intake factor ($cm^{-1}$).

### 3.2. Simulation Area

For simulating soil water movement under drip irrigation from single-point source, the coordinate origin was set at the emitter and the lengths of 40, 40 and 50 cm were taken along the horizontal x-, horizontal y- and vertical z-directions. For simulating soil water movement under drip irrigation from double-point source, the length of emitter spacing was taken along the horizontal x-direction, with one emitter located at the coordinate origin and the other at the end of the length along x-direction; the lengths of 40 and 50 cm were taken along the horizontal y- and vertical z-directions.

### 3.3. Boundary Conditions

During the experiment, the ponding area at the soil surface changed over time, which could be regarded as a dynamic-head boundary. Since Hydrus-3D can not simulate the dynamic-head boundary, this condition was regarded as a constant-head boundary according to previous studies [12, 13]. Additionally, the constant-head radius Rs was set as the ponding radius when surface ponding generally stabilized in the laboratory soil column experiment. Then the above boundary can be described as follows:

$$h=0\quad 0\leq\sqrt{x^2+y^2}\leq R_s,\ z=0,\ 0\leq t\leq T \tag{6}$$

The other boundaries were set as confining boundaries.

### 3.4. Initial Conditions

The initial soil water content measured before the start of the experiment was taken as the initial condition of water movement. This condition can be described as follows:

$$\theta(x,y,z,0)=\theta_0\quad 0\leq x\leq X,\ 0\leq y\leq Y,\ Z\leq z\leq 0,\ t=0 \tag{7}$$

### 3.5. Model Parameter Determination

Pedo-transfer functions were used to generate the hydraulic parameters of the van Genuchten model and obtain the preliminary parameters of the model. Then the basic parameters of the model were obtained by repeated calibration in accordance with experimental records were shown in Table

**Table 2. v-G model parameters of the experimental soil.**

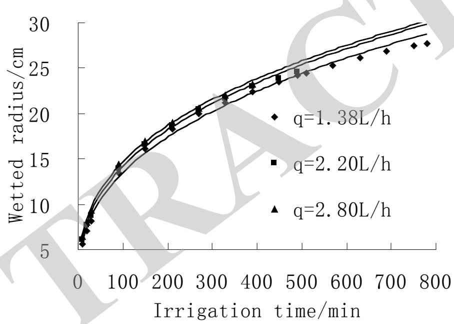
| Soil Classification | $\theta_s$ / (cm³/cm³) | $\theta_r$ / (cm³/cm³) | $\alpha$ / (1/cm) | $n$ | $K_s$ / (cm/min) |
|---|---|---|---|---|---|
| Latosol | 0.3362 | 0.0274 | 0.0332 | 1.4006 | 1.96 |

**2**. According to the experimental observations, the infiltration radius were 6.5 cm, 8 cm, 9 cm at the emitter discharge rates of 1.38, 2.20 and 2.80 L/h, respectively.

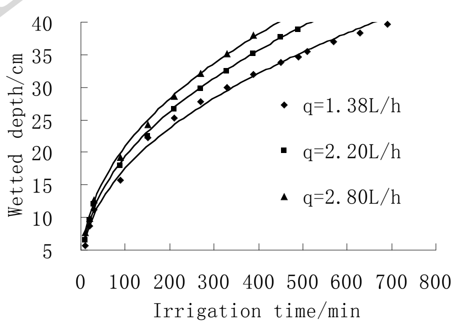
## 4. RESULTS

### 4.1. Experimental Data Analysis

Fig. (**1**) illustrated the relationship between wetting front migration and irrigation time under drip irrigation at the emitter discharge rates of 1.38, 2.20 and 2.80 L/h (irrigation volume 18 L). Clearly, emitter discharge rate affected the wetted depth greatly, but had little effect on the wetted radius. During the same irrigation time, the wetted depth increased with increasing emitter discharge rate to a greater degree than did wetted radius. Under irrigation of the same volume, emitters with a greater discharge rate resulted in slightly shorter wetted radius and depth than did emitters with a slightly smaller discharge rate immediately after the completion of irrigation. However, the differences were not significant since the total irrigation time was shorter for emitters with a greater discharge rate. During the same irrigation time, the wetted depth was 1.3–1.5-fold the wetted radius, indicating more significant infiltration in the vertical direction. The wetted radius and depth exhibited a power function relationship with irrigation time.




**a**. Wetted radius




**b**. Wetted depth

**Fig. (1).** Exponent relationship between wetting front migration and drip irrigation time at different emitter discharge rates (L/h).

### 4.2. Model Accuracy Analysis

First, we compared wetting front migration between the simulated and measured results. Fig. (**2**). presented the measured and simulated distances of soil wetting front from the point source at different irrigation time (discharge rate 1.38 L/h, volume 18 L). There was clearly a gap between the measured and simulated values of the wetting front at the initial stage of irrigation. The simulated wetting front moved faster than the measured one at 30, 90 min. Especially, the simulated values of the wetted radius were 2–3 cm greater than the measured values at the same irrigation time. At the late stage of irrigation, the gap between the measured and simulated values was gradually diminished with increasing irrigation time and almost disappeared at the irrigation time of 150 min.

The model overestimated wetting front migration mainly because Hydrus-3D could not simulate the moving-head boundary condition and thus regarded it as a constant-head boundary condition in the simulation. Additionally, the infiltration radius was set as the ponding radius when surface ponding generally stabilized in the laboratory soil column experiment. As a matter of fact, the ponding radius gradually changed before reaching the stable state, and the actual ponding radius was smaller than the simulated values before the stable state. Therefore, the measured values of the wetting front were smaller than the simulated values at the initial stage of irrigation, which accounted for the shorter distance of wetting front migration in the measurements than in the simulations. As the time elapsed, the difference between the measured and simulated values was gradually diminished and almost disappeared. Therefore, the simulated results of wetting front migration could better reflect the actual situation at the irrigation time more than 150 min.

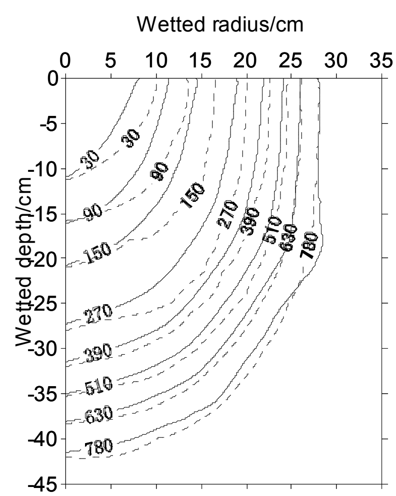
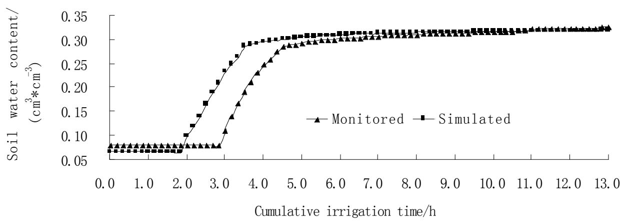
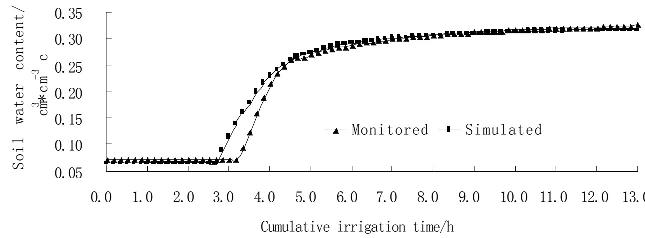


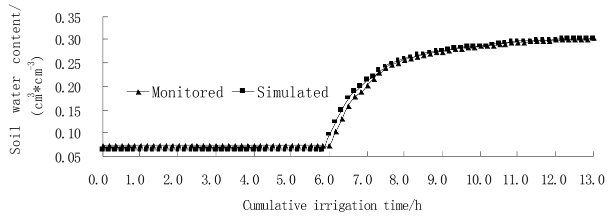

**Fig. (2).** Measured (solid) and simulated (dashed) shapes of the wetting front at different irrigation time (min).



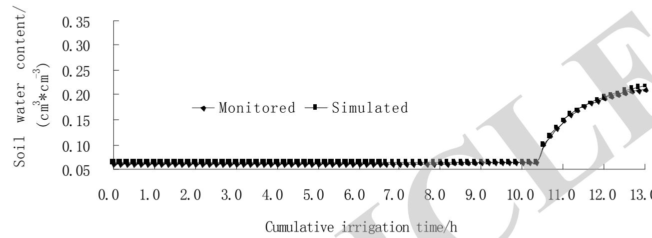

**a**. Probes buried at 5 cm depth




**b**. Probes buried at 15 cm depth




**c**. Probes buried at 25 cm depth




**d**. Probes buried at 35 cm depth

**Fig. (3).** Monitored and simulated water contents of the wetted soil volume at different irrigation time (h).

Next, we compared the simulated and actual irrigation volumes and examined the difference in soil water content at four monitoring points between the simulated and measured results. According to statistics, the irrigation volume during model calculation was 4.48 L. Since the simulation area accounted for 1/4 of the wetted soil volume, the simulated single-emitter irrigation volume was 17.92 L. The experimental irrigation volume was 9.0 L. Since the experimental area accounted for 1/2 of the wetted soil volume, the actual single-emitter irrigation volume was 18.0 L. There was a minor difference of 0.44% between the simulated actual irrigation volumes, which met the accuracy requirement.

Fig. (**3**) showed the changes in the monitored and simulated soil water contents over time at 5, 15, 25 and 35 cm depths with 15 cm horizontal distance from the emitter (single-emitter irrigation volume 18 L). On balance, the monitored and simulated values of soil water content followed similar trends at the four monitoring points. However, the time of the starting point of the changes showed difference between the monitored and simulated values. Such difference was gradually diminished with increasing depth of the monitoring point. With 15 cm horizontal distance from the emitter, the arrival time of the simulated wetting front was earlier than the than the monitored result by 1 h at 5 cm depth were shown in Fig. (**3a**), by 0.5 h at 15 cm depth were shown in Fig. (**3b**) and by 0.17 h at 25 cm depth were shown in Fig. (**3c**); the arrival time of the simulated wetting front was generally consistent with the monitored result at 35 cm depth were shown in Fig. (**3d**).

As mentioned earlier, the dynamic-head boundary condition was regarded as a constant-head boundary condition in model simulation. Thus, the simulated values of wetting front migration were greater than the measured values at the initial stage of irrigation. The simulated wetting front arrived earlier than the monitored wetting front at the point closer to the emitter, but this time difference was diminished gradually with increasing irrigation time. Once soil water content entered a stable state, the errors between the simulated and measured results were 1.7% at 5 cm depth, 2.6% at 15 cm depth, 0.5 % at 25 cm depth and 3.0% at 35 cm depth. The accuracy of the model simulation completely met the requirements of irrigation decision, and the simulated results of soil water content could exactly reflect the changes in the actual soil water content.

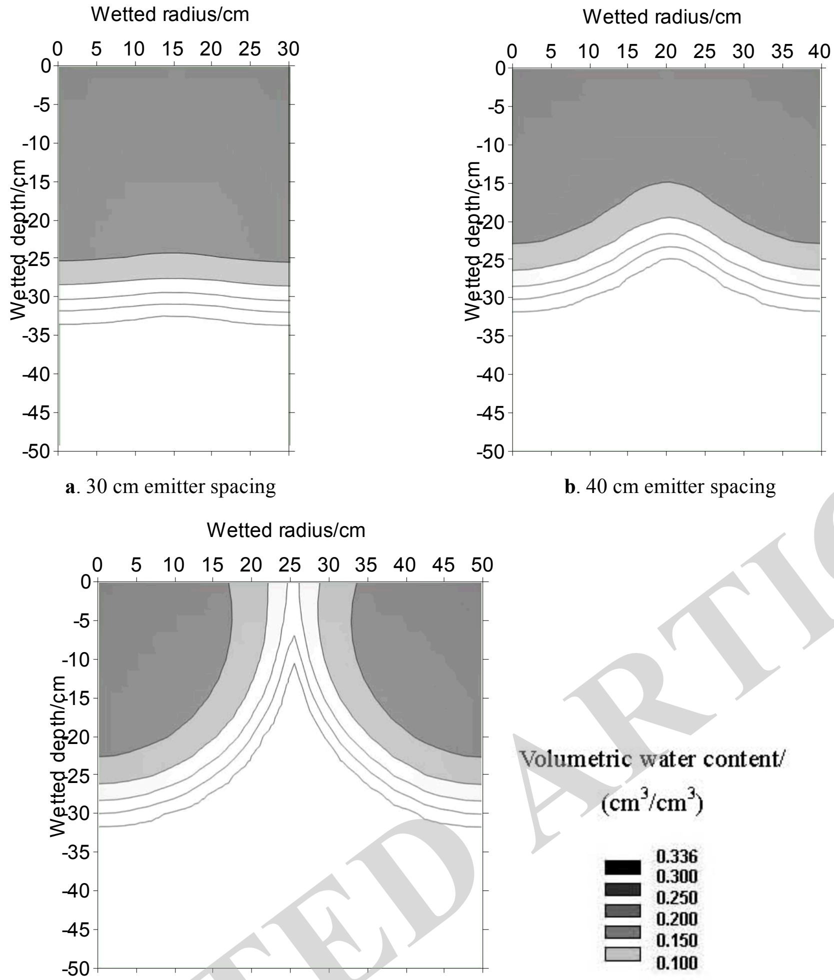
In summary, the simulation results of the proposed model could accurately reflect the actual situation of wetting front migration and soil water content changes when drip irrigation lasted more than 270 min.

Additionally, sugarcane is a crop characterized by drill sowing, shallow roots, and close-planting. The cropping pattern of wide-narrow rows (wide row spacing 1.2–1.3 m; narrow row spacing 0.4–0.5 m) is commonly used in sugarcane fields with drip irrigation. It has been reported that sugarcane roots are mainly distributed in the 0–20 cm (62%) and 20–40 cm soil layers (23.4%); the optimal irrigation depth and width for sugarcane of the vigorous growth stage are approximately 30 and 40 cm, respectively.

### 4.3. Effect of Emitter Spacing on Irrigation Uniformity

Emitter spacing is an important parameter of drip irrigation system design. We used Hydrus-3D to build a model of water movement under drip irrigation from double-point source. The irrigation conditions were as follows: emitter discharge rate 1.38 L/h, single-emitter irrigation volume 5.5 L, and emitter spacing 30, 40 and 50 cm. Fig. (**4**). showed a simulated water content distribution in the wetted soil volume at different emitter spacing by the end of irrigation.

The results showed that emitter spacing was an important factor affecting irrigation uniformity for drip irrigation in latosol of sugarcane field. At the emitter spacing of 30 cm, the wetted depth was 33.5 cm and the irrigation uniformity appeared good; the wetted soil volume formed a wetting zone with consistent wetted depth and uniform water distri-




**a**. 30 cm emitter spacing

**b**. 40 cm emitter spacing

**c**. 50 cm emitter spacing

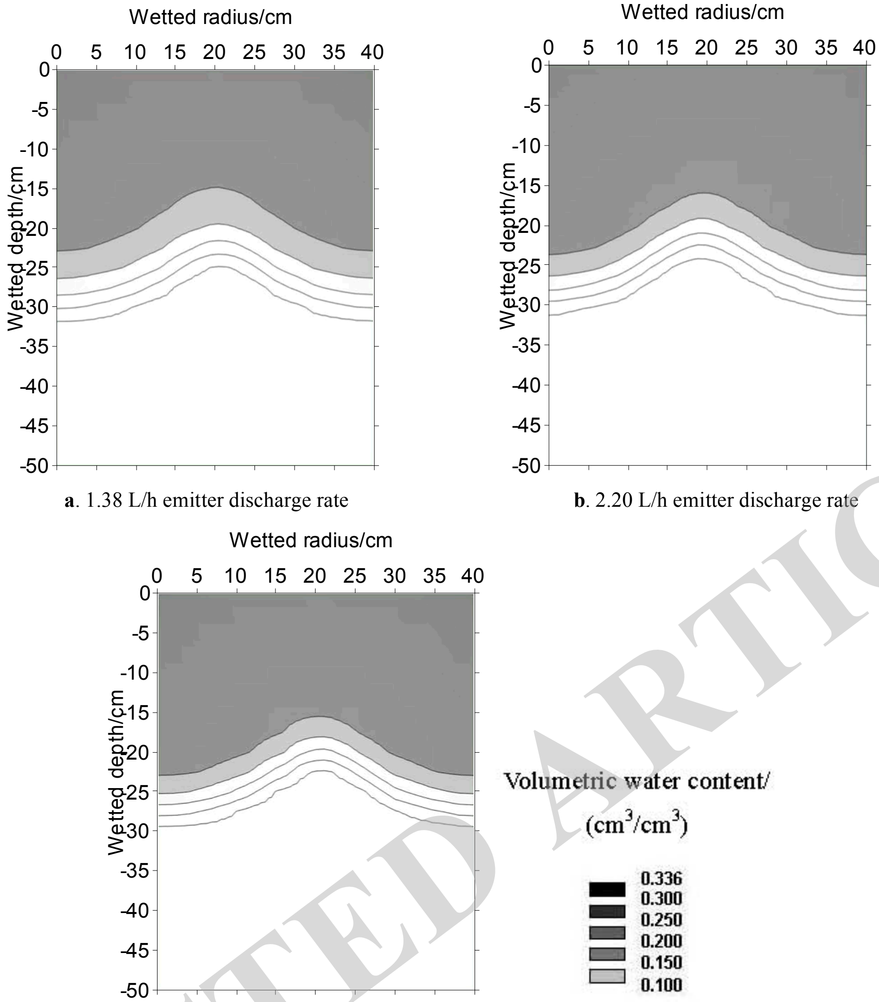
**Fig. (4).** Simulated water content distribution in the wetted soil volume under drip irrigation at different emitter spacing.

bution were shown in Fig. (**4a**). At the emitter spacing of 40 cm, the wetted depth directly below the emitter was 31.5 cm, while that directly below the midpoint of two emitters was 25 cm, with a 6.5 cm difference; the change in the shape of the wetting front was 20.6%, indicating the poor irrigation uniformity were shown in Fig. (**4b**). At the emitter spacing of 50 cm, the wetted depth directly below the emitter was 31.5 cm, while that directly below the midpoint of two emitters was only 10 cm, with a 21.5 cm difference and 68.3% change in the shape of the wetting front; water content in the core area of the wetted soil volume directly below the midpoint of two emitters was 0.153, significantly lower than that directly below the emitter which was 0.332; these results were indicative of the worse irrigation uniformity were shown in Fig. (**4c**). Since the cropping pattern of sugarcane (drill sowing and close planting) has higher demand for irrigation uniformity, we recommend the emitter spacing of 30 cm for drip irrigation at the emitter discharge rate of 1.38 L/h in latosol of sugarcane field.

### 4.4. Effect of Emitter Discharge Rate on Irrigation Uniformity

Emitter discharge rate is another important parameter of drip irrigation system design. We used Hydrus-3D to build a model of water movement under double-point source of drip irrigation with the following parameters: emitter spacing 40 cm, single-emitter irrigation volume 9 L, and emitter discharge rate 1.38, 2.20 and 2.80 L/h. Fig. (**5**). Showed a simulated water content distribution in the wetted soil volume at different emitter discharge rates by the end of irrigation.

The results showed that emitter discharge rate had little effect on irrigation uniformity in latosol of sugarcane field. Under irrigation of the same volume, emitters with a greater discharge rate had a shorter irrigation time and thus resulted in a smaller wetted volume, slightly increasing the irrigation uniformity. At the emitter discharge rate of 1.38 L/h, the wetted depth directly below the emitter was 31.5 cm, while that below the midpoint of two emitters was 25 cm; the 6.5 cm difference accounted for 20.6% change in the shape of the wetting front were shown in Fig. (**5a**). At the emitter discharge rate of 2.20 L/h, the wetted depth directly below the emitter was 31.0 cm, while that below the midpoint of two emitters was 24 cm; the 6.0 cm difference accounted for 19.4% change in the shape of the wetting front were shown in Fig. (**5b**). At the emitter discharge rate of 2.80 L/h, the wetted depth directly below the emitter was 29.0 cm, while that below the midpoint of two emitters was 23.5 cm; the 5.5 cm difference accounted for 19.0% change in the shape of




**a**. 1.38 L/h emitter discharge rate

**b**. 2.20 L/h emitter discharge rate

c. 2.80 L/h emitter discharge rate

**Fig. (5).** Simulated water content distribution in the wetted soil volume under drip irrigation at different emitter discharge rates.



the wetting front were shown in Fig. (**5c**). Therefore, it is infeasible to improve irrigation uniformity by a greater emitter discharge rate in latosol of sugarcane field.

From the perspective of project cost, using a smaller emitter discharge rate at the same emitter spacing can significantly reduce project investment. However, the irrigation time will need to be increased to obtain the same irrigation volume. Hence, both the project cost and operational management should be taken into consideration in order to select the appropriate emitter discharge rate.

### 4.5. Reasonable Parameter Analysis of Drip Tapes in Latosol of Sugarcane Field

Based on the above analysis, three combinations of emitter discharge rate and spacing (1.38, 2.20 or 2.80 L/h and 30 cm) enable common drip tapes to meet the requirement of irrigation uniformity in latosol of sugarcane field in Guangxi. The combination of lower emitter discharge rate (1.38 L/h) and 30 cm emitter spacing is most cost effective, while the combination of higher emitter discharge rate (2.80 L/h) and 30 cm emitter spacing is most expensive and time efficient, and thus is the easiest to manage. Given that the single-emitter irrigation volume desired for sugarcane of the growing period is 9 L in latosol, then one rotational irrigation group needs the irrigation time of 6.5 h at the emitter discharge rate of 1.38 L/h, 4.1 h at the emitter discharge rate of 2.20 L/h, and 3.2 h at the emitter discharge rate of 2.80 L/h.

According to the existing management system for sugarcane fields, two rotational irrigation groups are completed in one day. The operator needs to manually control the valve in the field for the changing over between rotational irrigation groups, and the pre-set control time is at least 0.5 h. Hence, the selection of emitter discharge rate at 1.38, 2.20 or 2.80 L/h leaves enough time for field control of the valve by the operator. The corresponding 1-d cumulative running time was 13, 8.2 and 6.4 h. Since rainfall is abundant in Guangxi, sugarcane fields are generally irrigated at a relatively low frequency (10–12 times a year). If using the emitter discharge rate of 1.38 L/h, the 1-d cumulative running time of the irrigation system is estimated to be 13 h. This strategy can be recommended as the preferential option as it not only complies with the regulatory requirements but also fits the work schedule of sugarcane farmers and meets general requirements of irrigation management. For sugarcane fields with special requirement for 1-d cumulative running time of the irrigation system, the appropriate emitter discharge rate should be determined in accordance with the single-emitter irrigation volume and running time.

Taking into consideration the project cost and operational management pattern, we recommend the following reasonable design parameters of common drip tapes for use in latosol of sugarcane fields in Guangxi: emitter discharge rate 1.38 L/h, emitter spacing 30 cm, and single-emitter irrigation volume 9 L.

## CONCLUSION

Emitter spacing strongly affected irrigation uniformity in latosol of sugarcane field. An emitter spacing of 30 cm ensured irrigation uniformity, while the emitter spacing of 40 or 50 cm resulted in poor irrigation uniformity in the experimental soil. Hence, drip tapes with 30-cm emitter spacing are recommended for irrigation of sugarcane cropped in the drill sowing and close planting pattern.

Emitter discharge rate had little effect on irrigation uniformity in latosol of sugarcane field. The appropriate emitter discharge rate should be selected by taking into consideration the project cost and operational management requirements.

In accordance with the project cost, operational management pattern, and water demand of sugarcane, the appropriate design parameters of drip tapes for irrigation of latosol under sugarcane were determined: emitter discharge rate 1.38 L/h, emitter spacing 30 cm, and single-emitter irrigation volume 9 L.

## CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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