APPLICATION OF CHEMICALS THROUGH A TRICKLE SYSTEM FOR SOIL-BORNE PEST CONTROL. I. DERIVATION OF BASIC PHYSICAL THEORY FOR PRACTICAL USE

J.C.W. Keng[1] and T. Vander Gulik[2]

[1]Research Station, Agriculture Canada, Agassiz, British Columbia V0M 1A0; and [2]Engineering Branch, B.C. Ministry of Agriculture and Food, Abbotsford, B.C. V2S 2C5

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High-frequency trickle irrigation has long been used in crop root zone water and nutrient management. Agricultural chemicals for soil-borne pest control, such as nematicides, may also be applied through a trickle system. The distribution of applied pesticide(s) may be confined by the designed wetting pattern. The quantitative treatments of two-dimensional water movement from line source water application were examined. Two simplified equations were derived to calculate the vertical wetting depth and horizontal wetting distance, respectively, in system design. Design case analysis based on various practical field situations was presented.

INTRODUCTION

The concept of trickling or dripping as a method of irrigating crops has become a common practice in commercial agricultural production in recent years. In general, trickle/drip irrigation is being used on orchards, vegetable and small fruit crops, vineyards and nurseries. Trickle systems can apply water directly into the root zone in small quantities and with high frequency. Losses by run-off and deep percolation may be minimized and waterlogging can be avoided. Trickle irrigation often increases crop yields and results in higher economic returns because of the high irrigation efficiency and low labor cost.

Another potential advantage of this precisely controllable water delivery system is its use for the application of agricultural chemicals, such as plant nutrients and/or pesticides. Desired chemicals may be applied directly and only to the soil surface near the base of the plant. Effective results may be realized with considerable reduced quantities of chemicals. Soil-water pollution caused by irrigation and the residual effect of applied chemicals may then be minimized.

However, due to the complicated nature of soil-water movement from a trickle source and the specific use of various agricultural chemicals, this promising potential of trickle systems has not been exploited extensively by either engineers or researchers. Applied herbicide, for example, is usually preferred to cover a wide area of soil surface, while other pesticides, such as nematicides, need to reach out to the deepest portion of the active root zone. A thorough understanding of the physics of soil-water flow from a trickle source is essential in predicting water-soluble chemical movement in soils.

The purposes of this paper are (1) to examine the basic physics and develop simplified equations to predict the flow pattern of a trickle system and (2) to suggest design and application procedures for trickling chemicals into soil.

Theory

The wetting depth and wetted surface area are the two most important factors determining the success of a particular pesticide treatment or the efficiency of fertilizer use when trickle irrigating with chemicals. When applying pesticides or fertilizers, properly controlled wetting depth would ensure adequate chemical treatment of the plant root zone and also prevent groundwater contamination through deep percolation. In the case of herbicide application, proper management of the wetted surface area would maximize weed control and avoid chemical damage to the plant, especially during the early growing stage.

1. Expansion of wetted surface areas

Assume Darcy's law applies in both saturated and unsaturated zones. Since infiltration involves only wetting, soil water content at any point in the system will always be increasing with time, and therefore, both water suction and the hydraulic conductivity of the soil are continuous functions of soil water content.

As observed under field conditions with in-line source water application, a strip of saturated zone develops in the vicinity of the trickle tubing shortly after irrigation starts. The width of the strip increases with time but the rate of increase (dX/dt) decreases as time progresses. Based on this observation Brandt et al. (1971) developed an analytical solution to describe the growth of wetted surface area for a line water source:

In an X-Y-Z rectangular Cartesian coordinate system, if the trickle tubing is placed at the origin (0,0) along the Y-axis, then water flows both horizontally along the X-axis and vertically downward in the Z-axis. The flow may be assumed planar with respect to the Y-axis.

The flow equation in two-dimensional forms is as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\theta)\frac{\partial P}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] \quad (1)$$

where θ is the volumetric moisture content, t is time, z is the vertical depth pointing downward, x is the horizontal distance normal to the tubing, P is the matric suction of the soil, H is the hydraulic head (the sum of gravitational and matric suction heads), and K is the hydraulic conductivity which is a function of the soil wetness.

The water content (θ) at a specified time (t) and position (x,z) is governed by Eq. 1. The initial and boundary conditions for (x,z,t) are as follows:

(1) $\theta(x,z,0) = \theta(x,z)$, when $t = 0$.

where θ is the initial soil moisture content; W is the unit volume within the boundaries specified here.

(2) $\frac{\partial \theta}{\partial z} = 0$, at $z = Z$, $0 \le x \le X$, $0 \le t \le T$

$\frac{\partial \theta}{\partial x} = 0$, at $x = 0$, $x = X$, $0 \le z \le Z$, $0 \le t \le T$

where Z,X, are arbitrary depth and horizontal distance beyond the wetting front. T is the end time of infiltration.

(3) $\theta = \theta_s$ in $0 \le X \le \Phi(t)$, $Z = 0$, $0 \le t \le T$

where $\Phi(t)$ is the width of the ponded strip in time (t).

$$\Phi(t)\left[K_s \frac{\partial H}{\partial Z} dx\right] = \tfrac{1}{2}q(t) \quad (2)$$

K_s is saturated conductivity. $q(t)$ is the water discharged per unit length of porous tubing.

(4) At $z = 0, 0 \leq t \leq T$.

By integrating Eq. 2 becomes

$$K_s\delta\Phi(t) = \tfrac{1}{2}q(t) \quad (3)$$

where $\delta = \left(H\frac{\partial P}{\partial Z}\right)_{Z=0}$ is the average surface pressure head across the saturated zone which may range from 1.0 in heavy soils to 2.5 in coarse sand. For all practical purposes, δ values are: clay loam or silty loam, δ = 1.0-1.5; loam, δ around 1.5; sandy loam δ = 2.0; sandy soil, δ = 2.5. By rearranging, Eq. 3 becomes:

$$\Phi(t) = \frac{q(t)}{2\delta K_s} \quad (4)$$

From Eq. 4 it is clear that $\Phi(t)$ is proportional to the discharging rate, q, and inversely proportional to the saturated hydraulic conductivity, K_s. Note: $\left(\frac{\delta H}{\delta Z}\right)_{Z=0}$ is not a constant; however, the average of $\left(\frac{\delta H}{\delta Z}\right)_{Z=0}$ can be treated as a constant when the surface flux approaches constant.

Equation 4 has been tested in both field and laboratory (Bresler et al. 1971; Keng et al. 1978) and was found suitable for a wide range of soils where evapo-transpiration (ET) loss during the application period is negligible. For areas with high ET rate, the right side of Eq. 4 should read:

$$\frac{q(t) - \mathrm{ET}(t)}{2\delta K_s}$$

2. Advance of wetting depth

The vertical advance of the wetting-front $Z(t)$ of plane flow pattern has been found to be linearly related to the square root of irrigation time, $t^{0.5}$ (Hachum 1976; Keng et al. 1982). Therefore, the one-dimensional downward infiltration equation, as used in furrow irrigation calculating may be applied in line source trickle irrigation. Equation 1 in one dimensional, unsaturated flow form can be rewritten to:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial\theta}{\partial Z}\right) - \frac{\partial K(\theta)}{\partial Z}$$

$$= \frac{\partial K(\theta)}{\partial Z}\left(D\frac{\partial\theta}{\partial Z}\right) - \frac{\partial K(\theta)}{\partial Z} \quad (5)$$

where D is diffusivity.

To solve Eq. 5, Philip (1969) developed a method of power series:

$$Z(\theta, t) = \sum_{n=1}^{\infty} fn(\theta)t^{n/2} = f_1(\theta)t^{1/2} + f_2(\theta)t$$

$$+ f_3(\theta)t^{3/2} + \ldots \quad (6)$$

under the conditions:

$t = 0, Z > 0, \theta = \theta_0$

$t > 0, Z = 0, \theta = \theta_s$

where θ_0 is the initial soil moisture content of the profile and θ_s is the saturated moisture content.

Since the power series converges rapidly, only the first term is significant in all practical calculations. Therefore its simplified solution is

$$Z = St^{1/2} \quad (7)$$

The S value is a mathematic parameter reflecting both soil sorbtivity and water application rate. Hachum (1976) in his study of plan flow found that

$$S = \epsilon q(t) + e \quad (8)$$

where ϵ and e are soil constants and may be determined in the laboratory. By compiling and rearranging Eqs. 7 and 8 become

$$t^{1/2} = Z/(\epsilon q(t) + e) \quad (9)$$

Equation 9 is used to determine trickle discharge rate or application time for wetting the soil to a desired depth.

Design Examples

CASE 1. Nematicide treatment for mature raspberry plants through a trickle system.

BACKGROUND. A severe nematode infestation was found in a 7-yr-old raspberry field, located on an upland sandy loam soil in the Fraser Valley, B.C. A nematologist recommended "Furadan," a soil pesticide, to control the nematodes. Nematode counts using root samples indicated large spatial variation of nematode population in the field, therefore, blanket application of Furadan would be costly and not necessary. In addition, excessive use of Furadan may cause other environmental concerns. The engineers were asked to design a trickle system for effective treatment.

PROCEDURES

Step 1. Find the volume of soil to be treated. Field investigation showed that the active root zone (feeder roots) extended up to 80 cm horizontally from the plant and to 15 cm deep. Therefore, pesticide need only be applied to the region of an 80 cm × 2 cm = 160-cm-wide strip centered on the row and to the depth of 15 cm.

Step 2. Determine soil physical parameters: (a) Measure saturated hydraulic conductivity, K_s. K_s of the soil was found to be in the magnitude of 5.0 × 10^{-3} cm.sec^{-1} or 0.3 cm.min^{-1}. (b) Laboratory sorbtivity experiment, using two different water application rates: Q_1 = 1.2 mL.min^{-1}.cm^{-1} length and Q_2 = 0.2 mL·min^{-1}·cm^{-1} indicated that S values were S = 1.01 and S = 0.37.

From Eq. 8

$$\epsilon S = q(t) + e$$

the values of ϵ and e were calculated as ϵ = 0.87 and e = 0.62.

Step 3. Choose application time, t, and rate, Q. To minimize labor and field operation time, an application time, t, of less than 2 h was preferred. In this case, t = 90 min was chosen.

Use Eq. 9 $t = Z/(\epsilon q(t) + e)$ where Z = 15 cm, ϵ = 0.87, and e = 0.62.

The discharge rate was calculated as $q(t)$ = 1.1 mL·cm^{-1}·min^{-1} which means, an application rate of 1.1 mL·cm^{-1}·min^{-1} is needed in order to apply the pesticide to 15-cm depth within 90 min.

Step 4. Check application time, t, and rate, $q(t)$. The application time, t, and rate, $q(t)$, should be checked against Eq. 4 to satisfy the requirement of surface wetted zone. Where $q(t)$ = 1.1 mL·cm^{-1}·min^{-1}, δ = 2.0, K_s = 3.0 × 10^{-1} cm·min^{-1}, $\Phi(t)$ is calculated equal to 82.5 cm.

Therefore, trickle emitters with a discharge rate of 1.1 mL·cm^{-1}·min^{-1} and application time of 90 min should be chosen for effective nematode treatment in the raspberry field.

CASE 2. Nematicide application via existing system.

BACKGROUND. Same as Case 1, except that a trickle irrigation system using twin-wall trickle tubing with a discharge rate of 0.6 mL·min^{-1}·cm^{-1} is already being employed for irrigation.

Step 1 and Step 2. Same as Case 1.

Step 3. Since discharge rate is fixed at 0.6 mL·cm^{-1}·min^{-1}, application time t may be calculated, using Eq. 9

$$t^{1/2} = 15/(0.6 \times 0.87 + 0.62) \text{ or } t = 172 \text{ min.}$$

Check with Eq. 4

$$\phi = \frac{q(t)}{2\delta K_s} = \frac{0.6 \cdot 172}{2 \cdot 2 \cdot 0.3} = 86 \text{ cm}$$

Therefore, an application time of roughly 3 h would be needed.

CASE 3. Determine quantities of nematicide and water to be applied.

A concentration of 5-10 ppm of carbofuran (2,3-dihydro-2,2-dimethyl-7 benzoforanyl methylcarbamate) in the root zone is required to control the nematode