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HYDRAULICS OF PERFORATED IRRIGATION TRAIL TUBE[a]

Discussion by James R. Gilley[2] and Jan Feyen[3]

The author presented a methodology for calculating the hydraulics of trail tubes for center-pivot irrigation systems. While he mentioned several possible difficulties with trail tube irrigation, and stated that they have potential benefits in energy saving and improvements in water-use efficiency, additional clarification and analysis are required before the procedures he presented can be used for the rational design of such systems.

First and most importantly, a potential error in the analysis should be mentioned and discussed. The author used the two-term infiltration model of Philip to describe the water intake beneath a center-pivot irrigation system. The assumption of one-dimensional infiltration with surface saturation at time zero is implicit in the application of this infiltration model, though not stated by the author. Thus, for this equation to be satisfactorily used for the case of parallel trail tubes described in the paper, the tubes must be close enough together to provide sufficient lateral water movement from the tubes to simulate one-dimensional flow. The trail tube spacing necessary to insure the one-dimensional conditions is, of course, a function of the flow rate of the trail tubes and the depth of irrigation to be applied (or speed of the system), as well as the soil properties. The flow conditions existing in trail tube irrigation, while not precisely the same, are similar to the unsteady flow from parallel line source trickle irrigation systems. An analysis of these types of irrigation systems, at least under time-dependent linearized conditions, has been described by Lomen and Warrick (11).

The two-term infiltration model used in the paper is valid for one-dimensional flow, but requires modification to account for the incomplete soil surface wetting that may be present under trail tube systems. The procedure used to describe the effective one-dimensional infiltration for furrow irrigation systems (8) might also be used for trail tubes. Thus, the infiltration model now becomes

$$D_A = (A_0 T_A^{0.5} + A_1 T_A) \frac{W_L}{W} \quad \text{(43)}$$

in which D_A = net depth of applied water; T_A = time of application or the time period for a point of the irrigated land to receive the applied water; W = spacing between adjacent trail tubes; W_L = wetted distance perpendicular to the trail tube (hereafter called the wetted diameter); and A_0 and A_1 = infiltration parameters of the infiltration model. Also implied in the development of this model is the condition that $W_L = W$, if $W_L > W$. Eq. 43 can now be used to calculate the proper trail tube length using the author's procedures. However, the variable W_L is difficult to evaluate and, as mentioned later, is a function of the trail tube discharge, irrigation depth and soil properties. The following procedure is suggested as a means of calculating the proper trail tube length.

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Tube Discharge Rate

The flow rate required at each trail tube location is a function only of the tube location, tube spacing, system length and system flow rate. As shown in the paper by Kincaid and Heermann (10), this relationship can be written as

$$Q_o = \frac{2\,Q\,r\,W}{R^2} \qquad (44)$$

in which Q_o = total tube flow rate; Q = total flow rate of the irrigation system; r = radial distance from the pivot point to the trail tube; and R = total length of the system. Eq. 44, to be used to calculate the total tube flow rate (Q_o), is a more fundamental relationship than Eq. 9.

The flow rate of center-pivot irrigation systems is often selected to meet the crop water requirement, either at the peak rate or a lesser rate based on the probability of rainfall and stored soil moisture. In either case, Eq. 44 can be rewritten as

$$Q_o = 2\,\pi r\,W\,S_c \qquad (45)$$

in which S_c = system capacity of the center-pivot system often expressed as mm d^{-1}.

Trail Tube Length

The equation to calculate the proper length of the trail tube can be found by combining Eqs. 7 and 9. Namely

$$L = \frac{Q_o T_A}{D_A W} \qquad (46)$$

which can now be used to calculate the correct trail tube length.

The trail tube flow rate (Q_o), needed in Eq. 46, is calculated from Eq. 45 using known values for r, W and S_c. The tube length can be calculated from Eq. 46 by using the value of T_A determined from Eq. 43. We are now faced with the problem of determining the proper value of the variable W_L. One method for calculating W_L incorporates the results of Lomen and Warrick (11), who developed a linearized form of the two-dimensional infiltration problem to determine the distribution of water content or pressure head from line source trickle irrigation systems by assuming certain relationships of the soil properties. These two relationships are

$$K = K_o \exp(\alpha h) \qquad (47)$$

and $$k = \frac{dK}{d\theta} \qquad (48)$$

in which K = soil hydraulic conductivity; K_o = saturated hydraulic conductivity; h = soil pressure head (expressed negatively); α = soil empirical constant with units of L^{-1}; k = soil constant with units of LT^{-1}; and θ = volumetric moisture content.

The solutions for two-dimensional infiltration by Lomen and Warrick (11) can be used to estimate the wetted diameter of the trail tube (W_L). One problem remains, however. The calculation of W_L, as expected, de-

TABLE 1.—Example Using Author's Soil and Center-Pivot System

Parameter (1)	Value (2)
R	396.24 m
r	396.24 m
D_A	25.4 mm
T_R	3 days
W	1.524 m
A_0	33.9 mm $h^{-0.5}$
A_1	17.4 mm h^{-1}

pends upon the unit discharge of the tube (Q_o/L). This complicates the calculation of the tube length (L), as the solution is now trial and error. The following steps summarize the trial and error solution.

The variables r, W, S_c and D_A, and all soil properties are given. The steps are:

1. Estimate a value of W_L (guess).
2. Calculate Q_o using Eq. 45 and the known values for r, W and S_c.
3. Calculate T_A using Eq. 43 and the known values for D_A, W, W_L and the soil properties.
4. Calculate L from Eq. 46 using values for Q_o, T_A, D_A and W.
5. Estimate W_L using the relationships and procedures found in Lomen and Warrick (11). This requires redrawing the curves presented by Lomen and Warrick (11) and using their dimensionless parameters to estimate the distance at which the pressure head reaches the selected value. This distance is used for the value of W_L.
6. Continue the process until the estimated value of W_L agrees with the calculated value.

Table 1 demonstrates the foregoing procedure, using the same soil and center-pivot system as that used by the author. Additional soil parameters for the 1.0 intake family soil are $K_o = 70$ cm/day; $\alpha = 0.08\ \text{cm}^{-1}$; $k = 325$ cm/day; and critical pressure head for wetting front = -20 cm.

For this system, the system capacity = 25.4 mm/3 days = 8.47 mm d^{-1}. From Eq. 45, the tube flow rate is $Q_o = 2\ \pi r\ W\ S_c = 0.372\ \text{Ls}^{-1}$. Using the trial-and-error procedure described earlier, the value for W_L is approximately 38 cm. From Eq. 43, the value of T_A is 2.67 h and from Eq. 46, the value of L is 92.3 m. Without the correction for the wetted diameter of the trail tube given in Eq. 43, the author found the length of the tube to be 11.5 m. Without this correction, the procedures described by the author can lead to significant errors.

For example, the calculated values of W_L ranged from 32–40 cm for irrigation depths ranging from 10–30 mm, respectively. A comparison of the trail tube lengths estimated by the two procedures is given in Fig. 6. To reduce the required trail tube length, the tubes' spacing must be reduced or the wetted diameter must be increased. Reducing the tube spacing while reducing the tube length would also increase the number of tubes required. Larger wetted diameter emitters ("spitters") could be installed in the trail tube depending on the inlet pressure available. This

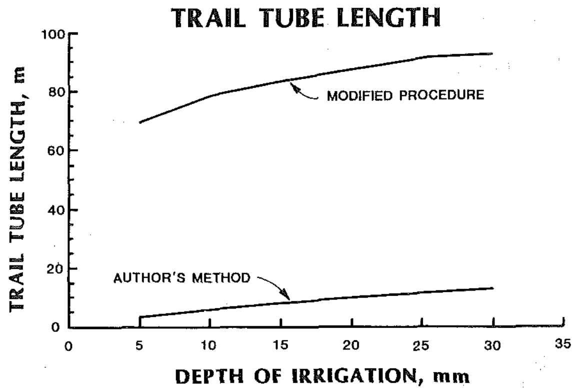

FIG. 6.—Required Trail Tube Length at Distance of 396 m for Center-Pivot Irrigation System 396 m in Length (Flow Rate of 8.47 mm/day and Tube Spacing of 1.524 m on Soil of Intake Family 1.0)

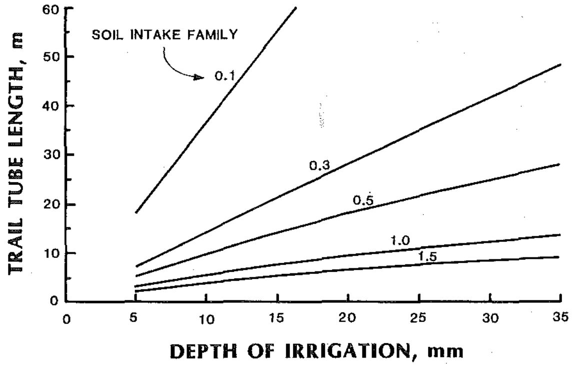

FIG. 7.—Required Trail Tube Length at Distance of 396 m for Center-Pivot Irrigation System 396 m in Length (Flow Rate of 8.47 mm/day and Tube Spacing and Wetted Diameter of 1.524 m for Various Soil Types)

technique would increase the wetted area, thereby allowing use of the original one-dimensional theory.

Even if the one-dimensional infiltrational model is acceptable in practice, relatively long tube lengths will be required for satisfactory operation. Calculated tube lengths on other soil types for the center-pivot system used as an example, assuming complete water coverage ($W_L = W$), are shown in Fig. 7. For fine textured soils (intake families of 0.1 and 0.3), relatively long tube lengths are required for proper soil infiltration. For these soils, either narrow tube spacings or larger wetted diameters are required. Howell and Phene (9) also concluded that frequent small applications are required for lateral-move irrigation systems on low-intake soils and practical lateral lengths between 10 and 20 m. This would be especially true for trail tubes at the end of the center-pivot systems, where larger flow rates are required.

The proper tube length is a function of the irrigation depth (Figs. 6 and 7). Thus, it is important that the largest perceived irrigation depth be chosen for design. The resulting tube lengths for these depths would, of course, be satisfactory for smaller irrigation depths.

The design procedures for the calculation of the spacing of the holes along the trail tubes presented by the author is commendable. However, Howell and Phene (9) found that while the "gradient" source system, similar to that described by the author, appeared interesting, the field experiment did not show an apparent advantage. Furthermore, the trickle draglines caused several mechanical problems resulting mostly from a large power requirement to pull the lines.

While trail tube irrigation as described by the author may offer some potential benefits, further analysis and field testing are required before it can become an economical substitute for existing low-pressure technology on center-pivot irrigation systems. The writers look forward to further papers in this area.

APPENDIX.—REFERENCES

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Closure by Shu-Tung Chu[4]

It is not proper to treat the trail tube as a narrow line source similar to a trickle irrigation tube. Fig. 8 shows the water application from a full-size trail tube demonstration model on Agricultural Engineering Research Farm, at South Dakota State University, in Brookings. The water delivered from a trail tube reaches a distance of 2 m or more on either side of a tube. Such a "wetted diameter" is 10 times the amount calculated by J. R. Gilley and J. Feyen in their discussion. Therefore their criticism on the writer's equation for calculating trail tube length does not appear to be justified.

Field tests conducted both at Brookings, a 24-tube system on the outer span of a 391-m center pivot system on a 0.5 intake family soil (Brookings series, 3–5% slope), and at Gettysburg (South Dakota), a 5-tube system on a linear-move irrigation system on a 1.0 intake family soil

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