Lecture 15

Maximizing Linear Move Field Length

I. The Procedure

- The following procedure for maximizing field length is from Allen, 1983, Univ. Idaho and Allen, 1990 (Irrig. Symp. Paper), and is used in the USUPIVOT computer program
- The basic strategy is to examine different application depths and different w values to maximize the area covered by the sprinkler system, and or to minimize labor requirements

1. Calculate the maximum application depth per irrigation ($d_x \leq MAD*Z*W_a$). Note that the maximum application depth may be less than $MAD*Z*W_a$ with an automatic system to maintain optimal soil water conditions and to keep soil water content high in case of equipment failure (i.e. don't need to take full advantage of TAW)

$$f' = d_x/U_d \text{ (round down to even part of day)}$$

2. Calculate net and gross application depths:

$$d_n = f\,(U_d)$$

$$d = d_n/E_{pa}$$

3. Calculate the (presumed) infiltrated depth per irrigation:

$$(D_f)_{max} = d \cdot R_e$$

where $(D_f)_{max}$ is the maximum depth to be evaluated, and assuming no runoff

4. For a series of 10 or so infiltration depths, d_f, beginning with d_f equal to some fraction (say 1/10) of $(D_f)_{max}$:

$$d_f = (i/10)(D_f)_{max} \quad \text{where } i = 1 \text{ to } 10$$

and,

$$f' = d_f\, DE_{pa}/(100\, U_d)$$

f = f' - days off (days off may be zero because the system is automatic), where f' = irrigation frequency for depth d_f. DE_{pa} is used here (in percent) because U_d is net, not gross

5. Determine the maximum AR_x for a particular d_f value using the following two equations (assuming an elliptical pattern):

$$AR_x = \frac{\left(1 - \frac{(SF)(AR_x)}{k}\right)\left(k^{\frac{1}{n+1}}(n+1)^{\frac{n}{n+1}}(D - SS - c)^{\frac{n}{n+1}}\right)}{\sqrt{1.05 - 1.6\left(\frac{\pi}{2}\right)^2\left(\frac{D}{d_f} - 0.5\right)^2}} \qquad (301)$$

where,

$$D = \left(\frac{\left(1.05\,AR_x^2 - 1.6\,AR_x^2\left(\frac{\pi}{2}\right)^2\left(\frac{D}{d_f} - 0.5\right)^2\right)^{-0.5}\left(-1.6\,AR_x^2\left(\frac{\pi}{2}\right)^2\left(\frac{D}{d_f} - 0.5\right)\right)}{d_f\, n\left(1 - \frac{(SF)(AR_x)}{k}\right)\left((n+1)^{\frac{-1}{n+1}}\right)\left(k^{\frac{1}{n+1}}\right)}\right)^{-n-1} + SS + c \qquad (302)$$

and AR_x is the peak application per pass (mm/min); D is the applied depth at time t = ∫ (AR) dt (mm); SS is the allowable surface storage (after ponding) before runoff occurs (usually less than about 5 mm); c is the instantaneous soil infiltration depth, from SCS soil intake families (mm); k is the coefficient in the Kostiakov-Lewis equation; and d_f is the total depth of water applied to the ground surface (mm)

- The parameter “n” is defined as: n = a -1, where “a” is the Kostiakov exponent (see NRCS soil curves at www.wcc.nrcs.usda.gov/nrcssirrig)
- Note that SS is a function of the field topography and micro-topography, and is affected by foliar interception of applied water
- These last two equations have π in them because there is an inherent assumption of an elliptical water application profile from the sprinklers or sprayers
- Recall that $AR_{av} = (\pi/4)AR_x$ for an elliptical pattern

- SF is a relative sealing factor (in terms of soil water infiltration), and may have values in the range of 0 to about 0.36

- The higher values of SF tend to be for freshly tilled soils, which are generally most susceptible to surface sealing from the impact of water drops
- Lower values of SF are for untilled soils and vegetative cover, such as alfalfa or straw, which tend to reduce the impact of water drops on the soil and help prevent runoff too
- If the linear move irrigates in both directions (no deadheading), then d_f is one-half the value from these two equations

6. Compute the total wetting time, t_i, in minutes:

$$t_i = \frac{d_f}{\frac{\pi}{4}\left(AR_x\right)} \tag{303}$$

7. Compute the speed of the system for the required t_i:

$S = w/t_i$ (m/min) (w is for a specific nozzle type)

If $S \geq S_{max}$ (this may occur for a high intake soil or for a very light application with surface storage) then reduce the application rate and increase time as follows:

$$t_i = \frac{w}{S_{max}} \tag{304}$$

$$AR_x = \frac{4\,d_f}{\pi\,t_i} \tag{305}$$

Thus,

$$S = S_{max} \tag{306}$$

8. Calculate maximum field length, X:

8(a). For irrigation in one direction, only (dry return, or deadheading):

$$X = \frac{60\,f\,T - 2\,t_{reset}}{\left(\frac{1}{S_{wet}} + \frac{1}{S_{dry}} + \frac{t_{hose}}{100}\right)} \tag{307}$$

where,

X = maximum length of field (m);
f = system operating time per irrigation (days);
T = hours per day system is operated (21-23);
t_{reset} = time to reset lateral at each end of the field (min);
t_{hose} = time to change the hose (min/100 m);
S_{wet} = maximum speed during irrigation (m/min); and
S_{dry} = maximum dry (return) speed (m/min)

$$labor = \frac{2\,t_{reset} + 0.01X\left(t_{hose} + 2\,t_{super}\right)}{60\,f} \tag{308}$$

where labor is in hrs/day; and t_{super} is minutes of supervisory time per 100 m of movement

8(b). For irrigation in both directions (no deadheading):

$$X = \frac{60\,f\,T - 2\,t_{reset}}{2\left(\frac{1}{S_{wet}} + \frac{t_{hose}}{100}\right)} \tag{309}$$

and labor is calculated as above in 8(a)

9. Calculate the irrigated area:

$$Area_{max} = \frac{XL}{10{,}000} \tag{310}$$

where $Area_{max}$ is in ha; and L is the total lateral length (m)

10. Labor per hectare per irrigation, L_{ha}:

$$L_{ha} = \frac{labor}{Area_{max}} \tag{311}$$

11. Repeat steps 5-10 for a different value of d_f

12. Repeat steps 4-11 for a new w (different application device or different operating pressure)

13. Select the nozzle device and application depth which maximizes the field length (or fits available field length) and which minimizes labor requirements per ha

14. System capacity:

$$Q_s = \frac{\pi AR_x wL}{4k_3 R_e} \quad (312)$$

where k_3 = 96.3 for L and w in ft, Q_s in gpm, and AR_x in in/hr; and k_3 = 60 for L and w in m, Q_s in lps, and AR_x in mm/min

The system capacity can also be computed as:

$$Q_s = \frac{d_f wL}{t_i k_3 R_e} \quad (313)$$

II. Assumptions & Limitations of the Above Procedure

- In the above procedure (and in the USUPIVOT computer program), when designing for a system which irrigates in both directions, the second pass is assumed to occur immediately after the first pass, so that the infiltration curve is decreased due to the first pass before the AR_x of the second pass is computed
- This will occur near the ends of the field, where the design is most critical. The proposed procedure assumes that:

  - There is no "surge" effect of soil surface sealing due to a brief time period between irrigation passes (when irrigating in both directions)
  - The infiltration curve used represents soil moisture conditions immediately before the initiation of the first pass
  - The infiltration curve used holds for all frequencies (f) or depths (d_f) evaluated, while in fact, as f↑, θ↓, so that the Kostiakov coefficients will change. Therefore, the procedure (and field ring infiltration tests) should be repeated using coefficients which represent the Kostiakov equation for the soil moisture condition which is found to be most optimal in order to obtain the most representative results.

Linear Move Design Example

I. Given Parameters

- Hose-fed linear move, irrigating in only one direction in a 64-ha field (400 m wide and 1,600 m long)
- The pressure is 140 kPa (20 psi) for spray booms with a preliminary w if 10 m (33 ft)
- The soil infiltration characteristics are defined for the Kostiakov-Lewis equation as:

$$Z = 5.43\tau^{0.49} \tag{314}$$

with Z in mm of cumulative infiltrated depth; and τ is intake opportunity time in minutes. Other design parameters:

U_d = 7.7 mm/day
MAD = 50%
Z = 0.9 m
W_a = 125 mm/m

O_e = 1.00
R_e = 0.94
E_{pa} = 85%

- Maximum dry (returning) speed = 3.5 m/min
- Maximum wet (irrigating) speed = 3.0 m/min
- Reset time = 0.5 hours per end of field
- Hose Reset time = 10 min/100 m of travel distance
- Supervisory time = 5 min/100 m of travel distance

II. One Possible Design Solution

- This design will consider only spray booms with w = 10 m
- Note that the full procedure would normally be performed with a computer program or spreadsheet, not by hand calculations

1. Calculate the maximum application depth per irrigation [d_x = MAD(z)(W_a), or less]

$$d_x = (0.5)(0.9)(125) = 56 \text{ mm} \tag{315}$$

$$f' = \frac{d_x}{U_d} = \frac{56}{7.7} = 7.3 \Rightarrow f' = 7 \text{ days} \tag{316}$$

2. Net and gross application depths:

$$d_n = f\,U_d = (7)(7.7) = 54 \text{ mm} \tag{317}$$

$$d = \frac{d_n}{E_{pa}} = \frac{54}{0.85} = 64 \text{ mm} \tag{318}$$

3. Infiltrated depth at each irrigation:

$$D_f = d R_e = (64)(0.94) = 60 \text{ mm} \tag{319}$$

4. For a series of 10 infiltration values, calculate d_f, beginning with $d_f = D_f$ /10:

$$d_f = D_f\left(\frac{i}{10}\right) \tag{320}$$

where i = 1 to 10. For this example, let i = 4 and, d_f = (0.4)(60 mm) = 24 mm. Then,

$$f' = \frac{d_f\,DE_{pa}}{U_d} = \frac{(24)(0.85/0.94)}{7.7} = 2.8 \text{ days} \tag{321}$$

Assume no days off (no down time during the peak use period)

$$f = f' - \text{days off} = 2.8 - 0 = 2.8 \text{ days} \tag{322}$$

5. Determine the maximum AR_x for the particular d_f depth:

From Eq. 282:

AR_x = 0.97 mm/min

AR_x reaching the soil surface = 0.97 (R_e) = 0.91 mm/min

6. Compute the total wetting time, t_i, in minutes:

$$t_i = \frac{4\,d_f}{\pi\,AR_x} = \frac{4(24)}{\pi(0.91)} = 34 \text{ min} \tag{323}$$

7. Compute the speed of the system for the required t_i:

$$S = \frac{w}{t_i} = \frac{10}{34} = 0.3 \text{ m/min} \quad (324)$$

Thus, $S < S_{max}$ (3.0 m/min), so this is OK.

8. Calculate maximum field length, X:

For irrigation in one direction, only (deadhead back):

$$X = \frac{60 f T - 2 t_{reset}}{\left(\frac{1}{S_{wet}} + \frac{1}{S_{dry}} + \frac{t_{hose}}{100} \right)} = $$

$$= \frac{60(2.8)(22) - 2(30)}{\left(\frac{1}{0.3} + \frac{1}{3.5} + \frac{10}{100} \right)} = 970 \text{ m} \quad (325)$$

and, the labor requirements are:

$$\frac{2 t_{reset} + 0.01\left(t_{hose} + 2 t_{super}\right) X}{60 f} = $$

$$= \frac{2(30) + 0.01[10 + 2(5)][970]}{60(2.8)} = 1.5 \text{ hrs/day} \quad (326)$$

where t_{reset} is the reset time at the end of the field (min); t_{hose} is the hose reconnection time (min/100 m); and t_{super} is the “supervisory” time (min/100 m)

9. Maximum irrigated area:

$$Area_{max} = XL/10000 = 970(400)/10000 = 38.8 \text{ ha}$$

which is only about half of the actual field area!

10. Labor per ha per irrigation, L/ha:

$$L/ha = (labor/area)_{max} = 1.5/38.8 = 0.039 \text{ hr/ha/day}$$

11. Repeat steps 5 - 10 for a new d_f (not done in this example)

12. Repeat steps 4-11 for a new w (different application device or operating pressure). (not done in this example).

13. Select the nozzle, device and application depth that maximizes the field length (or fits the available field length), and which minimizes labor requirements per ha.

Note: 38.8 ha << 64 ha, which is the size of the field, (970 m << 1600 m which is the length of the field). Therefore, it is important to continue iterations (steps 11 and 12) to find an application depth and or new w (different sprinkler or spray device) to reach 1600 m and 64 ha, if possible.

Additional Observations:

- For a 6-m spray boom, applying a 12-mm depth per each 1.4 days would almost irrigate the 64 ha. However, the labor requirement is doubled, as the machine must be moved twice as often. This additional cost must be considered and weighed against the larger area irrigated with one linear move machine.
- If larger spray booms were used (w = 16 m rather than 10 m) (these would be more expensive) then 18 mm could be applied each 2.1 days, and all 64 ha could be irrigated with one machine.
- If low pressure impact sprinklers were used (these would be less expensive than spray booms, but energy costs would be higher), then w = 22 m, and 30 mm could be applied each 3.5 days (more water can be applied since the application rate is spread over a wider area from the lateral), and all 64 ha could be irrigated. In addition, ET_c would be less since the soil would be wetted less often. Also, the soil intake rate would be higher each irrigation because of a drier antecedent moisture at the time of irrigation.
- Notice that required wetting time for rotation times (f) greater than 2 days are identical between all types of spray devices. This is because, for the large depths applied, a minimum wetting time is required. The system speed is adjusted to fit the w value of the water application device.
- If no acceptable solution for this problem were found, then alternatives to be evaluated would be to irrigate in <u>both</u> directions, or to consider a ditch-fed linear move (this requires a leveled ditch, but does not required time for moving hoses and hose friction losses).
- You could also consider a “robot” controlled machine that automatically connects alternating arms to hydrants on a buried mainline (but this is a very expensive alternative)
- You might begin to wonder whether an investment in a linear move machine is justifiable when there is a significant labor requirement for reconnecting the supply hose, resetting at the end of the field, and

supervising operation. That is, why not put in a center pivot or a side roll system instead?

- If one linear move cannot cover the entire field length in the available period, "f" (days), you could consider two linear move machines for the same field

14. System Capacity:

$$Q_s = \frac{\pi A R_x w L}{4 k_3 R_e} = \frac{\pi (0.91)(10)(400)}{4(60)(0.94)} = 51 \text{ lps} \ \ (809 \text{ gpm}) \tag{327}$$

alternatively,

$$Q_s = \frac{d_f w L}{t_i k_3 R_e} = \frac{(24)(10)(400)}{(33.6)(60)(0.94)} = 51 \text{ lps} \ \ (809 \text{ gpm}) \tag{328}$$

Note that the computed Q_s is larger than one based strictly on U_d and T, because the machine is shut off during reset and hose moving

For Q_s based only on f, A, d and T, with no consideration for t_{hose},

$$Q_s = 2.78 \frac{A d}{f T} = 2.78 \frac{(38.3)(24)}{(2.8)(22)(0.94)} = 44 \text{ lps} \ \ (700 \text{ gpm}) \tag{16}$$

But this flow rate is too low – it does not consider hose moving and reset time. So, the 51 lps system capacity should be used for design