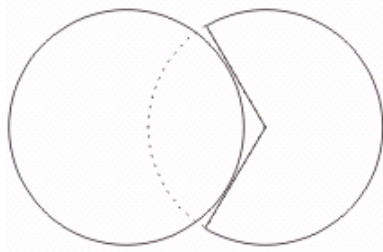


## Lecture 12

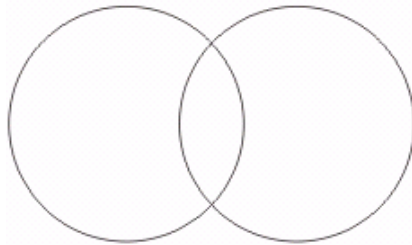
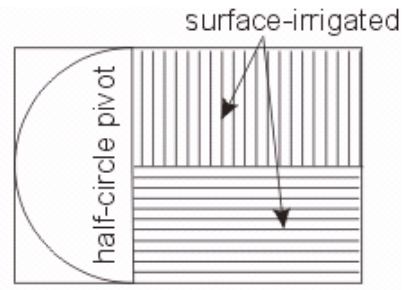
# Center Pivot Design & Operation

### I. Introduction and General Comments

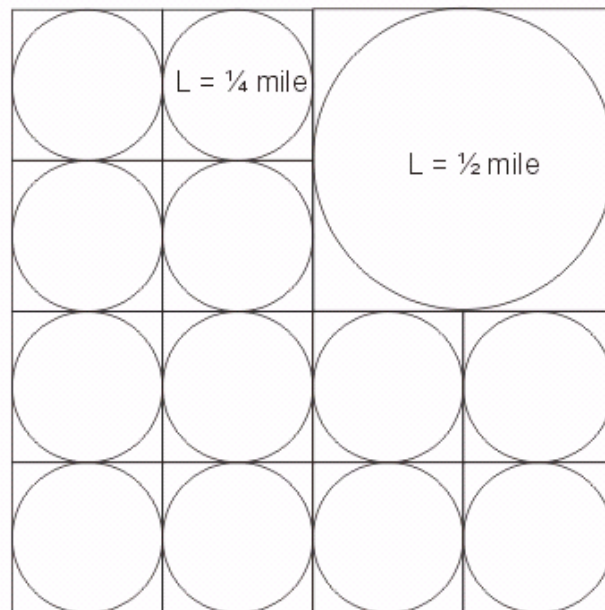
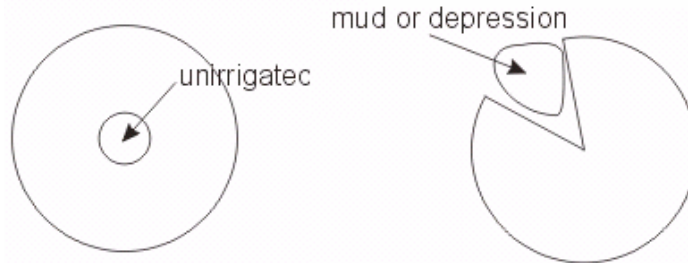
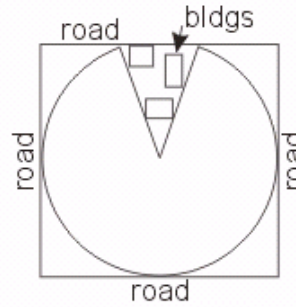
- Center pivots are used on about half of the sprinkler-irrigated land in the USA
- Center pivots are also found in many other countries
- Typical lateral length is 1,320 ft (400 m), or ¼ mile
- The lateral is often about 10 ft above the ground
- Typically, 120 ft pipe span per tower (range: 90 to 250 ft), often with one-horsepower electric motors (geared down)
- At 120 ft per tower, a 1,320-ft lateral has about 10 towers; with 1-HP motors, that comes to about 10 HP just for moving the pivot around in a circle
- The cost for a ¼-mile center pivot is typically about \$55,000 (about \$435/ac or \$1,100/ha), plus about \$20,000 (or more) for a corner system
- For a ½-mile lateral, the cost may be about \$75,000 (w/o corner system)
- In the state of Nebraska there are said to be 43,000 installed center pivots, about 15% of which have corner systems
- Center pivots are easily (and commonly) automated, and can have much lower labor costs than periodic-move sprinkler systems
- Center pivot maintenance costs can be high because it is a large and fairly complex machine, operating under “field” conditions
- The typical maximum complete rotation is 20 hrs or so, but some (120-acre pivots) can go around in only about 6 hrs
- IPS 6” lateral pipe is common (about 6-5/8 inches OD); lateral pipe is generally 6 to 8 inches, but can be up to 10 inches for 2,640-ft laterals
- Long pivot laterals will usually have two different pipe sizes
- Typical lateral inflow rates are 45 - 65 lps (700 to 1,000 gpm)
- At 55 lps with a 6-inch pipe, the entrance velocity is a bit high at 3 m/s
- Typical lateral operating pressures are 140 - 500 kPa (20 to 70 psi)
- The end tower sets the rotation speed; micro switches & cables keep other towers aligned
- Corner systems are expensive; can operate using buried cable; corner systems don't necessarily irrigate the whole corner
- Without a corner system or end gun,  $\pi/4 = 79\%$  of the square area is irrigated
- For a 1,320-ft lateral (without an end gun), the irrigated area is 125.66 acres
- For design purposes, usually ignore soil WHC ( $W_aZ$ ); but, refill root zone at each irrigation (even if daily)
- Center pivots can operate on very undulating topography
- Some center pivots can be moved from field to field
- Below are some sample center pivot arrangements



one pivot full circle,  
the other partial circle



both full circle, overlapping





- Some pivots have an end gun that turns on in the corners, in which all other sprinklers shut off via individual solenoid-actuated valves. The pivot stops in the corner while the end gun runs for a few minutes.
- Others just slow down in the corners, turning on an end gun, but leaving the other sprinklers running (at lower discharges)
- Many farmers like extra capacity in the center pivot so they can shut off during windy times of the day, and still complete the irrigations in time
- Corner systems have angle detectors so that sprinklers in the corner arm turn on and off individually (or in groups) as the arm swings out and then back in again
- Center pivots have safety switches to shut the whole thing off if any tower gets too far out of alignment. Some also have safety switches to shut them off if the temperatures gets below freezing (ice builds up and gets heavy, possibly collapsing the structure). Some have safety switches connected to timers: if a tower has not moved in a specified number of minutes, the system shuts down. There may also be safety switches associated with the chemical injection equipment at the lateral inlet location.



- Center pivots on rolling terrain almost always have pressure regulators at each sprinkler
- Some engineers claim that center pivots can have up to about 90% application efficiency

## II. System Capacity

- The general center pivot design equation for system capacity is based on Eq. 5.4 from the textbook:

$$Q_s = K \frac{Ad}{fT} = \frac{R^2 d}{k_1 f T} = \frac{R^2 U_d k_f}{k_1 T E_{pa}} \quad (257)$$

where,

K is 2.78 for metric units and 453 for English units

$k_1$  is  $(3,600 \text{ s/hr})/\pi = 1,146$  for metric units; 30.6 for English units

$k_f$  is the peak period evaporation factor (Table 14.1 in the textbook)

A is area (ha or acre)

d is gross application depth (mm or inch)

f is frequency in days per irrigation

T is operating time (hrs/day)

R is the effective radius (m or ft)

$U_d$  is the peak-use ET rate of the crop (mm/day or inch/day)

$Q_s$  is the system capacity (lps or gpm)

- The gross application depth, d, is equal to  $d_n/E_{pa}$ , where  $E_{pa}$  is the design application efficiency, based on uniformity and percent area ( $pa$ ) adequately irrigated
- The operating time, T, is generally 20-22 hrs/day during the peak-use period
- R is the *effective* radius, based on the wetted area from the center pivot
- The effective radius is about 400 m for many pivots
- $R \approx L + 0.4w$ , where L is the physical length of the lateral pipe, and w is the wetted diameter of the end sprinkler
- This assumes that approximately 0.8 of the sprinkler radius beyond the lateral pipe is effective for crop production
- Note that, for center pivots,  $Q_s$  is proportional to  $U_d$ , and d and f are generally not used, which is similar to drip irrigation design

## III. Gross Application Depth

- If a center pivot is operated such that the water holding capacity of the soil is essentially ignored, and water is applied frequently enough to satisfy peak-use crop water requirements, then use  $d_n/f = U_d$ , and

$$d' = \frac{k_f U_d}{E_{pa}} = \frac{k_f U_d}{D E_{pa} R_e O_e} \quad (258)$$

where  $d'$  is the gross application depth (mm/day or inches/day); and  $k_f$  is a peak-use period evaporation factor, which accounts for increased soil and foliage evaporation due to high frequency (daily) irrigation

- When  $LR > 0.1$ , the  $LR$  can be factored into the equation as:

$$d' = \frac{0.9k_f U_d}{(1-LR)DE_{pa}R_eO_e} \quad (259)$$

which is the same as Eq. 14.1b from the textbook, except that  $DE_{pa}$ ,  $R_e$  and  $O_e$  are all as fractions (not percent)

- Values of  $k_f$  can be selected for the peak period from Table 14.1 of the textbook for varying values of frequency,  $f$
- Values for non-peak periods can be computed as described in the textbook on page 314:

$$k'_f = (k_f - 1) \frac{(100 - PT')/PT'}{(100 - PT)/PT} + 1.0 \quad (260)$$

where  $k_f$  and  $PT$  are for the peak-use period (Table 14.1), and  $k'_f$  and  $PT'$  are the frequency coefficient and transpiration percentage ( $PT$ ) for the non-peak period

$$PT = \frac{T}{ET} \quad (261)$$

- $PT$  and  $PT'$  can be thought of as the basal crop coefficient ( $K_{cb}$ ), or perhaps  $K_{cb} - 0.1$  (relative to alfalfa, as per the note in Table 14.1)
- It represents the transpiration of the crop relative to an alfalfa reference

#### IV. Water Application along the Pivot Lateral

- A major design difficulty with a center pivot is maintaining the application rate so that it is less than the intake rate of the soil
- This is especially critical near the end of the lateral where application rates are the highest
- As one moves along the center pivot lateral, the area irrigated by each unit length of the lateral (each 1 ft or 1 m of length) at distance  $r$  from the pivot point can be calculated as:

$$a = \pi(r + 0.5)^2 - \pi(r - 0.5)^2 = 2\pi r \quad (262)$$

which is equal to the circumference at the radial distance  $r$

- The portion of  $Q_s$  (called  $q$ ) which is applied to the unit strip at distance  $r$  is:

$$\frac{q}{Q_s} = \frac{a}{A} = \frac{2\pi r}{\pi R^2} = \frac{2r}{R^2} \quad (263)$$

or,

$$q = \frac{2rQ_s}{R^2} \quad (264)$$

where  $q$  can be in units of lps per m, or gpm per ft

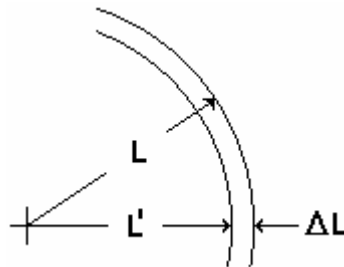
- This gives the amount of water which should be discharging from a specific unit length of lateral at a radial distance  $r$  from the pivot point
- The  $q$  value at the end of the lateral ( $r = R$ ) per ft or m is:

$$q_{\text{end}} = \frac{2Q_s}{R} \quad (265)$$

- Use  $q$  to select the nozzle size, where  $q_{\text{nozzle}} = q S_e$

## V. End-Gun Discharge

- This last equation is very similar to Eq. 14.20a, except for the omission of the  $S_j$  term
- Equation 14.20b is for the end gun discharge, assuming that the end gun is used primarily to compensate for the lack of pattern overlap at the end of the lateral
- Equation 14.20b can be justified as follows:



- Assuming the “basic” circle discharge,  $Q_b$ , includes the end gun discharge,  $q_g$ , we can write:

$$\frac{Q_b}{\pi L^2} \approx \frac{q_g}{\Delta L (2\pi L')} \quad (266)$$

or, perhaps more precisely,

$$\frac{Q_b}{\pi L^2} \approx \frac{q_g}{\Delta L (2\pi(L' + \Delta L/2))} \quad (267)$$

but  $\Delta L/2$  is generally very small compared to  $L'$ , and this is ostensibly assumed in Eq. 14.20b, so after solving the above for  $q_g$  you will arrive at Eq. 14.20b:

$$q_g \cong \frac{2L'\Delta L}{L^2} Q_b; \text{ for } \Delta L < 0.03L \quad (268)$$

## VI. Application Rate

- For a center pivot,  $S_e = 1$  (based on a unit distance along the lateral) and  $S_l = w$  (wetted width in the tangential direction), so the average application rate (called AR) at a distance  $r$  along the lateral is:

$$AR = \frac{k_3 2r Q_s R_e O_e}{R^2 w} = \frac{2\pi r k_f d R_e O_e}{60 f T w} = \frac{2\pi r U'_d R_e O_e}{60 T w} \quad (269)$$

where AR is the average application rate over width  $w$  (mm/min or inch/min);  $k_3$  is 1.61 for English units and 60 for metric units; and  $f$  is the time to complete one revolution (days)

- $w$  is equal to the wetted diameter of the spray or sprinkler nozzles on the lateral
- $U'_d$  is the gross daily irrigation water requirement (mm/day or inch/day) and includes the effect of  $k_f$

$$U'_d = \frac{k_f d}{f} = \frac{k_f (U_d - P_e)}{DE_{pa}} \quad (270)$$

- The three forms of the above equation assume a rectangular application pattern across the width  $w$  (that is, the application rate is uniform across  $w$ )
- Note that AR is proportional to  $r$  and is at a maximum at the end of the lateral
- Note that if  $w$  could be equal to  $2\pi r$ , the application rate would be equal to the gross application depth divided by the hours of operation per day (just like a fixed or solid-set sprinkler system) – but this is never the case with a center pivot machine

- At the end of the lateral ( $r = R$ ), the average application rate can be calculated as:

$$AR_{r=R} = \frac{2\pi R U'_d R_e O_e}{60 T w} \quad (271)$$

again, where a rectangular application pattern is assumed

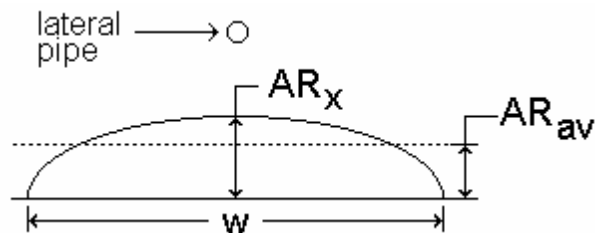
## VII. Application Rate with an Elliptical Pattern

- If the application pattern perpendicular to the lateral were elliptical in shape:

$$AR_x = \frac{4}{\pi} \left( \frac{2k_3 r Q_s R_e O_e}{R^2 w} \right) = \frac{4}{\pi} \left( \frac{2\pi r U'_d R_e O_e}{60 T w} \right) = \frac{r U'_d R_e O_e}{7.5 T w} \quad (272)$$

where  $AR_x$  is the maximum application rate (in the center of the pattern) ( $AR_x$  is in mm/min for  $U'_d$  in mm/day)

- In the above equation,  $k_3$  is 1.61 for English units, or 60 for metric units
- It is usually a better approximation to assume an elliptical pattern under the sprinklers than to assume a rectangular pattern, even though both are only approximations



- For example, if  $U'_d = 9$  mm/day (which includes  $k_f$ ),  $T$  is 22 hrs/day,  $w$  is 30 m,  $R$  is 400 m,  $R_e$  is 0.95 and  $O_e$  is 1.0, and the sprinkler application pattern is elliptical, then the maximum application rate at the far end of the lateral is:

$$AR_x = \frac{(400)(9)(0.95)(1.0)}{(7.5)(22)(30)} = 0.69 \text{ mm/min} \quad (273)$$

- $AR_x$  is the peak AR (at the top of the ellipse, or directly beneath the lateral), so an “average” ( $AR_{av}$ ) can be calculated, representing the average AR beneath the wetted area perpendicular to the lateral pipe
- The calculated value of 0.69 mm/min is 41.4 mm/hr, which could be tolerated only by a very sandy soil

- For a rectangular pattern,  $AR_{av} = AR_x$
- For an elliptical pattern,  $AR_{av} = (\pi/4)AR_x$
- Therefore, in the example,  $AR_{av} = (\pi/4)(0.69) = 0.54$  mm/min
- If  $d$  were 10 mm, it would take  $t_t = 10/0.54 = 18$  minutes to apply the water at the rate  $AR_{av}$ . (may want to use  $d R_e O_e$  instead of just  $d$  in such a calculation)
- $R_e$  can be taken from Fig. 6.8 or from examples in Table 14.3
- Guidelines for determining CI are given in Table 14.4
- The center pivot speed (at the end of the lateral) is  $w/t_t$ , where  $t_t$  is the time of wetting
- In the preceding example,  $w$  is 30 m and  $t_t$  is 18 min
- Therefore, the speed should be about  $30 \text{ m}/18 \text{ min} = 1.7 \text{ m/min}$  at the end
- Note that with spray booms,  $w$  is larger, and  $AR$  is smaller for the same  $q$  value