

A center pivot irrigation system is a movable pipe structure that rotates around a central pivot point connected to a water supply. Center pivot irrigation systems are the most popular sprinkler irrigation systems in the world because of their high efficiency, high uniformity, ability to irrigate uneven terrain (Fig. 12.1), and low capital, maintenance, and management costs. The history of center pivot irrigation systems began in Nebraska in the 1950s, and there are now hundreds of thousands of center pivot irrigation systems in the world. Center pivots are “perhaps the most significant mechanical innovation in agriculture since the replacement of draft animals by the tractor” (Splitter, *Scientific American*). The systems move through the field by electrically powered tractor wheels. Sprinkler flow rates increase toward the outer end of the pivot because the end of the pivot travels faster. The primary design constraint is the prevention of runoff at the end of the pivot, where application rates are highest. This chapter covers center pivot pipeline and main-line design, selection of sprinklers, and optimization of the design with respect to yield, energy requirement, components, and economics.

Center pivots irrigate large areas (50 ha or 160 ac). The huge green circles dot many agricultural regions (Fig. 12.2). As seen from the photograph, the major disadvantage of center pivots is that they don’t naturally irrigate the corners of fields.

Because center pivots are circular, 21.5 % of production is lost in the unirrigated corners. If land is inexpensive and water is limited (Fig. 12.3), then loss of production in the corners may not be of concern. However, if land is limited, then there are several methods to reduce, eliminate, or irrigate corners. Corner areas can be reduced by staggering the circles (Fig. 12.3), which requires large land areas that are not previously broken into square sections. Corner areas can be reduced or eliminated with extendable arms at the end of center pivots that swing out and irrigate corners. Corner areas are eliminated with linear move irrigation systems, which are like center pivots but travel linearly; however,

water is supplied to linear move system from lined concrete ditches or movable pipe systems, which are expensive and often difficult to maintain or operate. Big gun sprinklers (Fig. 12.4) at the end of the pivots can extend the entire irrigated circle of the pivot or can be turned on specifically in the corners.

---

### Sprinkler Types

The original center pivots had widely spaced high-pressure impact sprinklers mounted on top of the center pivot pipeline (Fig. 12.5). However, in order to reduce evaporation and pressure energy, many pivots now have drop tube sprayers (Fig. 12.3), which require less pressure (less energy) than top-mounted impact sprinklers. Low energy precision application sprinklers (LEPA) require even less energy (Fig. 12.6)

Sprinklers that hang below the pipe but are elevated above the crop canopy are called Mid-Elevation Sprinkler Application (MESA) sprinklers. The original MESA sprinklers have downward-facing nozzles that spray water onto flat or serrated plates (Fig. 12.7) and have a 13 m application diameter. Newer rotating sprinklers (Fig. 12.8) have a rotating stream with a much larger diameter of application (23 m) and a more uniform application pattern. In addition, droplets are larger so there is less evaporation; however, rotating sprinklers operate at 20 PSI (140 kPa) while serrated plate sprinklers only require 10 PSI (70 kPa).

Sprinklers with a larger application diameter are less prone to ponding and runoff because the application rate is lower. Because of their larger diameter, rotating sprinklers have an average application rate 60 % less than the serrated plate sprinkler. Impact sprinklers may have a 100 ft diameter (30 m) and thus only 20 % of the application rate of serrated plates (less runoff).

Low Energy Precision Application (LEPA) bubblers hang from drop tubes and are typically spaced two rows



**Fig. 12.1** Potato fields under irrigation with center-pivot sprinklers in Idaho, USA (Credit: US Army Corps of Engineers)

apart (1.5–2 m) in order to provide uniform water application to all plants, if not to the soil volume. LEPA systems have the lowest energy costs because they save water (reduce evaporation) and can operate between 6 and 10 PSI (40–70 kPa) pressure. LEPA bubblers flood the furrow so furrows must be diked every few meters with plastic furrow inserts or with a dammer diker tractor implement.

LESA (Low Elevation Spray Application) and LPIC (Low Pressure, In-Canopy) sprayers (Fig. 12.6) are between LEPA bubblers and MESA sprinklers. These sprinklers are popular in arid climates for crops such as alfalfa that are not planted in rows. In some applications, LESAs are used to germinate the crop and then modified after germination by adding a “sock,” which is a flexible plastic tube that fits over the sprayer and directs water down into the furrow. In low-profile crops such as alfalfa, LESAs are placed just above the canopy in order to minimize evaporation.

## Evaporation

Sprinkler droplet evaporation is a function of wind speed, vapor pressure deficit, sprinkler nozzle pressure and sprinkler nozzle diameter. Frost and Schwalen recorded the

depth of evaporation from sprinklers (not center pivot sprinklers) over a range of conditions, and they developed a nomograph to calculate percent evaporation. The nomograph was later converted to the following equation by Trimmer which is accurate in the midrange of the Frost and Schwalen nomograph:

$$L_e = \left[ \frac{1.98(D)^{-0.72} + 0.22(e_s - e_a)^{0.63}}{+3.6 \cdot 10^{-4}(h)^{1.16} + 0.14(U)^{0.7}} \right]^{4.2} \quad (12.1)$$

Where

$T$  = air temperature, °C

$RH$  = relative humidity, fraction

$e_s - e_a$  = vapor pressure deficit, kPa

$L_e$  = evaporation and wind drift, percent

$D$  = nozzle diameter, mm

$h$  = nozzle operating pressure, kPa

$U$  = wind velocity, m/s.

$$e_s - e_a = 0.61 \exp\left(\frac{17.27T}{T + 237.3}\right)(1 - RH) \quad (12.2)$$

The work of Frost and Schwalen was not calibrated for center pivots; however, the Trimmer equation is used in the

**Fig. 12.2** Satellite image of circular fields in center pivot area (Credit NASA)



**Fig. 12.3** Center pivot irrigation systems in the Sahara desert (Credit NASA)





**Fig. 12.4** Big gun at end of center pivot irrigation system (Credit NRCS)



**Fig. 12.5** Impact sprinklers on top of pivot

following example as a rough indication of evaporation rates from impact sprinklers mounted on top of center pivots.

**Example 12.1** What is the expected evaporation fraction for the following conditions (humid and arid climates) with impact sprinklers?

Condition 1. Arid climate

$$\begin{aligned} \text{RH} &= 10\%, T = 40^{\circ}\text{C}, D = 9/64''(3.57 \text{ mm}), U \\ &= 16 \text{ km/h}(4.44 \text{ m/s}), \text{ and } h = 70 \text{ psi}(490 \text{ kPa}) \end{aligned}$$

Condition 2. Humid climate

$$\begin{aligned} \text{RH} &= 90\%, T = 25^{\circ}\text{C}, D = 9/64''(3.57 \text{ mm}), U \\ &= 8 \text{ km/h}(2.22 \text{ m/s}), \text{ and } h = 70 \text{ psi}(490 \text{ kPa}) \end{aligned}$$

Condition 1. Arid climate

$$e_s - e_a = 0.61 \exp\left(\frac{17.27(40)}{40 + 237.3}\right)(1 - 0.1) = 6.63 \text{ kPa}$$



**Fig. 12.6** Drop tube sprayers

**Fig. 12.7** Serrated plate sprayer on drop tube (Credit NRCS)



$$L_e = \left[ \frac{1.98(3.57)^{-0.72} + 0.22(6.63)^{0.63} + 3.6 \cdot 10^{-4}(490)^{1.16}}{+ 0.14(4.44)^{0.7}} \right]^{4.2}$$

= 39%

$$L_e = \left[ \frac{1.98(3.57)^{-0.72} + 0.22(0.32)^{0.63} + 3.6 \cdot 10^{-4}(490)^{1.16}}{+ 0.14(2.22)^{0.7}} \right]^{4.2}$$

= 7.6%

If the droplet remains in the air longer than in the experiments used to derive Eq. 12.3, such as for a pivot, then spray evaporation losses would be more than 39 %.

Condition 2. Humid climate

$$e_s - e_a = 0.61 \exp\left(\frac{17.27(25)}{25 + 237.3}\right)(1 - 0.9) = 0.32 \text{ kPa}$$

Evaporation losses are clearly unacceptable in the arid climate. These results show why center pivot systems were not adopted in arid environments until the advent of LEPA and LESA systems.

In addition to droplet evaporation in the air, evaporation losses also include water that stays on the canopy and

**Fig. 12.8** Rotator on drop tube  
(Credit NRCS)



evaporates and water that evaporates from soil surface. It depends on depth of application, but a typical estimate is that 10 % of the applied water remains on the foliage. If another 12–15 % is lost to evaporation, then total loss would be 20–25 % water lost to evaporation. In contrast to higher elevation spray systems, LEPA systems have only 3–5 % evaporation loss (in arid climates), and LESA systems have a 12–15 % total evaporation loss in a high profile crop such as corn. Although direct water evaporation from droplets or the canopy may reduce the transpiration requirement of the crop, the evaporation loss in arid climates is unacceptable for top mounted impact sprinklers.

The following sections use the *Chapter 12 Center Pivot* program. An excellent center pivot design program called CPED (Center Pivot Evaluation and Design) was developed by NRCS and is available online. One advantage of CPED is that it has many component specifications.

### Center Pivot Pipeline Flow Rate

The entire center pivot flow rate is the product of gross application rate and irrigated area divided by the expected fraction of the day that the center pivot is running. The fraction is generally less than 1.0 due to repairs or crop management.

$$Q_p = 0.116 \frac{i_g A}{1 - L_{r-m}} \quad (12.3)$$

where

$Q_p$  = center pivot flow rate, L/sec

$L_{r-m}$  = fraction of down time for center pivot during peak ET, dimensionless

$A$  = Area of field, ha

$i_g$  = required gross application rate, mm/day

**Example 12.2** A 400 m radius center pivot irrigation system operates for 22 out of 24 hours per day. Calculate the required pivot flow rate if  $i_g = 16.2$  mm/day.

$$A = \pi r_{\max}^2 = \pi(400^2) (1 \text{ ha}/10,000 \text{ m}^2) = 50.3 \text{ ha}$$

$$Q_p = 0.116 \frac{i_g A}{1 - L_{r-m}} = 0.116 \frac{(16.2 \text{ mm}) (50.3 \text{ ha})}{1 - (2/24)} = 103 \text{ L/s}$$

The *CP\_infilt\_RO* worksheet in the *Chapter 12 Center pivot* program calculates pivot flow in cell B5.

|   | A                       | B           |
|---|-------------------------|-------------|
| 1 | Pivot length (radius)   | 400 m       |
| 2 | Pivot area              | 50.3 ha     |
| 3 | Hours per day operation | 22 hr       |
| 4 | Gross application req   | 16.2 mm/day |
| 5 | Pivot flow rate         | 103.0 L/sec |
| 6 | Normal gross app 24 hr  | 17.7 mm/day |

### Infiltration Rate and Application Rate

The most common constraint in center pivot design is prevention of runoff (Fig. 12.9) at the end of the pivot. If application rate exceeds the infiltration rate + soil surface storage, then there is ponding and runoff. The reason that the end is the critical location is that application rate is high because application time is low with the high rate of travel.

**Fig. 12.9** Ponding and runoff at end of pivot (Courtesy of NRCS)



The time of application,  $T_a$ , at the end of the pivot is proportional to the ratio of the sprinkler wetted diameter to center pivot circumference,  $2\pi r$ .

$$T_a = \left(\frac{D_w}{2\pi r}\right) T_r \quad (12.4)$$

where

- $D_w$  = sprinkler wetted diameter, m
- $T_r$  = time for one complete rotation of the pivot, hr
- $r$  = radius of the center pivot, m
- $T_a$  = application time for outer sprinkler, hr

Traditional pivots complete one rotation each day. However, new high velocity pivots complete three or more revolutions each day. The advantage of more frequent rotations and a smaller application depth per rotation is that even if infiltration rate is exceeded by application rate, the small depth of application is contained by soil surface storage capacity; thus, there is no runoff, and the water can slowly infiltrate into the soil after the pivot passes by. The disadvantage is that more evaporation takes place. For example, in Fig. 12.10 the high velocity LESA sprinkler application to alfalfa is held by surface depressions and surface crop residue. If there are no depressions, a steep slope, or no crop residue on the soil surface, then surface storage is low.

In this case, with a young crop, evaporation would be higher with multiple passes since the ground surface would be flooded for a greater percentage of time. The difference in evaporation would be more exaggerated at night since open pond evaporation continues in the night while plant evapotranspiration ceases at night. With a mature crop, there may be little difference in evaporation with multiple passes since evaporation from the ground surface is low in comparison to canopy transpiration.

**Example 12.3** A drop tube LESA sprayer has a 4 m wetted diameter ( $D_w$ ), and the time of rotation for the 400 m long pivot is 22 hours, calculate the time of water application for the last (outer) sprinkler on the center pivot pipeline.)

$$\begin{aligned} T_a &= T_r \left(\frac{D_w}{2\pi r}\right) = 24 \text{ hr} \left(\frac{4 \text{ m}}{2\pi(400 \text{ m})}\right) = 0.038 \text{ hr} \\ &= 2.29 \text{ min} \end{aligned}$$

This calculation is performed in cells E1:E5 in the *CP\_Infilt\_RO* worksheet.

|                    |      |              |
|--------------------|------|--------------|
| Sprinkler distance | 400  | m            |
| Wetted diameter    | 4    | m            |
| Rotation rate      | 24   | hrs rotation |
| Sprinkler app time | 2.29 | minutes      |
| Sprinkler spacing  | 2    | m            |

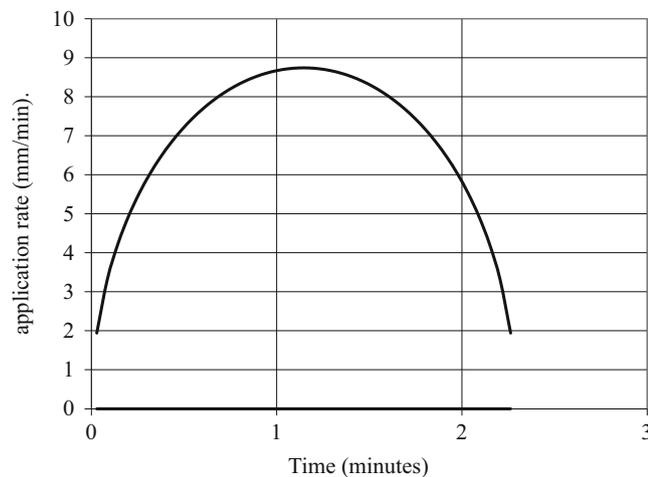
The application rate is not uniform over time. It is zero when sprinkler droplets first reach a point in the field, is a maximum when the sprinkler is directly overhead, and then decreases back to zero after the sprinkler passes by. The application rate vs. time curve is often modeled as an ellipse (Fig. 12.11) even though the actual shape of the application rate curve is often different from an ellipse.

$$\frac{\left(\frac{di}{dt}\right)^2}{\left(\frac{di}{dt}\right)_{\max}^2} + \frac{t^2}{(t_a/2)^2} = 1 \quad (12.5)$$

where

- $di/dt$  = instantaneous application rate, mm/min
- $t$  = length of time after a point is first wetted by the pivot, min
- $di/dt_{\max}$  = maximum application rate, mm/min.

**Fig. 12.10** Surface storage in level alfalfa field (Courtesy of NRCS)



**Fig. 12.11** Application rate versus time for point in the field with 2.1 minute application time

The application rate vs. time is calculated by rearranging Eq. 12.5 and solving for instantaneous application rate,  $di/dt$  (Fig. 12.11). In Eq. 12.6,  $t = 0$  when the application rate is maximum.

$$\left(\frac{di}{dt}\right) = \sqrt{\left(\frac{di}{dt}\right)_{\max}^2 \left(1 - \frac{t^2}{(\tau_a/2)^2}\right)} \quad (12.6)$$

Let  $t = 0$  when application begins by substituting  $t - T_a/2$  for  $t$ .

$$\left(\frac{di}{dt}\right) = \sqrt{\left(\frac{di}{dt}\right)_{\max}^2 \left(1 - \frac{(t - \tau_a/2)^2}{(\tau_a/2)^2}\right)} \quad (12.7)$$

The maximum application rate,  $di/dt_{\max}$  (mm/min) is found with the following equation [derived based on area of ellipse =  $\pi ab$ :  $2i_a = \pi (di/dt_{\max}) (T_a/2)$ ]. The net application depth  $i_a$  is the depth of water that reaches the soil ( $i_g$  minus evaporation).

$$\left(\frac{di}{dt}\right)_{\max} = \left(\frac{4}{\pi}\right) \left(\frac{i_a}{T_a}\right) \quad i_a = i_g(1 - L_e) \quad (12.8)$$

**Example 12.4** Plot the instantaneous application rate and calculate the maximum application rate for the end of the LESA pivot described in Examples 12.2 and 12.3:  $i_g = 17.7$  mm,  $T_a = 2.29$  min. The percent of sprinkler water that evaporates before it hits the soil is 11%.

$$i_a = i_g(L_e) = 17.7 \text{ mm}(1 - 0.11) = 15.7 \text{ mm}$$

$$\begin{aligned} \frac{di}{dt_{\max}} &= \left(\frac{4}{\pi}\right) \left(\frac{i_a}{T_a}\right) = \left(\frac{4}{\pi}\right) \left(\frac{15.73}{2.29}\right) = 8.74 \text{ mm/min} \\ &= 52 \text{ cm/hr} \end{aligned}$$

The net application rate and maximum application rate are calculated in cells H1:H3 in the *CP\_Infilt\_RO* worksheet.

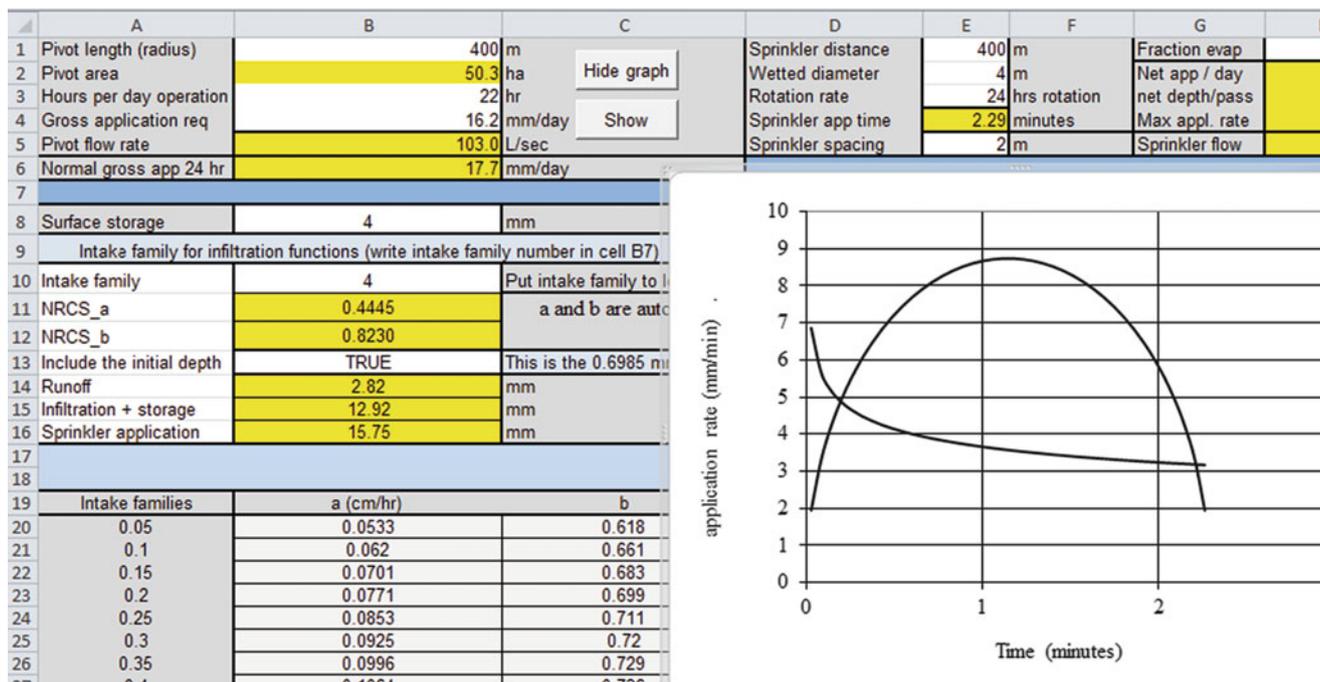


Fig. 12.12 Calculation of runoff and infiltration for intake family 4 soil in *CP\_Infilt\_RO* worksheet

| Cell | Parameter          | Value | Unit         |
|------|--------------------|-------|--------------|
| D1   | Sprinkler distance | 400   | m            |
| D2   | Wetted diameter    | 4     | m            |
| D3   | Rotation rate      | 24    | hrs rotation |
| D4   | Sprinkler app time | 2.29  | minutes      |
| D5   | Sprinkler spacing  | 2     | m            |
| F1   | Fraction evap      | 0.11  |              |
| F2   | Net app / day      | 15.73 | mm/day       |
| F3   | net depth/pass     | 15.73 | mm/pass      |
| F4   | Max appl. rate     | 8.74  | mm/min       |
| F5   | Sprinkler flow     | 1.030 | L/sec        |

Application rate vs. time (Fig. 12.11) is calculated with Eq. 12.7.

$$\left(\frac{di}{dt}\right) = \sqrt{\left(\frac{di}{dt}\right)_{\max}^2 \left(1 - \frac{(t - \tau_a/2)^2}{(\tau_a/2)^2}\right)}$$

$$= \sqrt{8.74^2 \left(1 - \frac{(t - 1.145)^2}{(1.145)^2}\right)}$$

The application rate vs. time is shown in Fig. 12.11 from the *CP\_Infilt\_RO* worksheet.

The application rate curve can be compared with the soil’s infiltration rate curve to determine whether the application rate exceeds the infiltration rate at any time during the application period. For example, an infiltration rate and application rate curve are shown in Fig. 12.12. The infiltration rate decreases as the soil fills with water. If any section of the application rate curve is greater than the infiltration rate curve, then ponding takes place.

The *CP\_Infilt\_RO* worksheet (Fig. 12.12) allows the user to select from the NRCS intake families listed in cells A20:C38. Enter the intake family in cell B10, and the coefficient and exponent are automatically changed in cells B11:B12. You can include the NRCS constant 0.6985 mm (see Chap. 3) by writing TRUE in cell B13. The surface storage depth is entered into cell B8, the depth of water that is stored in depressions on the soil surface during each pass. Functions in VBA then calculate the total runoff, infiltration + storage, and total depth of sprinkler application for each pass in cells B14:B16.

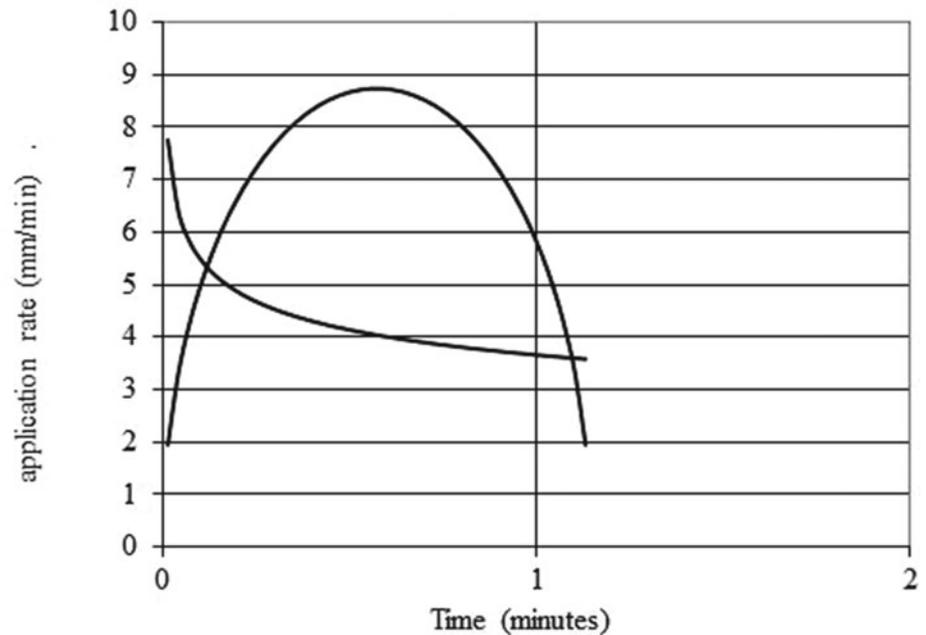
One way to extend the time of application,  $T_a$ , is the use of booms that extend out from the pivot pipeline with each boom holding several sprinklers. In order to prevent nonuniform application, the booms are angled diagonally from the pivot pipeline in order to offset boom sprinklers. Surface storage can be increased in order to prevent runoff. Tillage equipment can be used to increase soil surface roughness or cloddiness or crop residue can be used on the soil surface. field slope can significantly increase runoff as shown in Figure. For rough or cloddy ground, the NRCS estimates

**Fig. 12.13** Infiltration and storage calculation in CP\_Infiltr\_RO worksheet

|    | A  | B      | C                                 |
|----|--|--------|-----------------------------------|
| 8  | Surface storage  | 4      | mm                                |
| 9  | Intake family for infiltration functions (write intake family number in cell B7) |        |                                   |
| 10 | Intake family  | 4      | Put intake family to left         |
| 11 | NRCS_a   | 0.4445 | a and b are automatically updated |
| 12 | NRCS_b   | 0.8230 |                                   |
| 13 | Include the initial depth  | TRUE   | This is the 0.6985 mm infiltr     |
| 14 | Runoff   | 2.82   | mm                                |
| 15 | Infiltration + storage   | 12.92  | mm                                |
| 16 | Sprinkler application  | 15.75  | mm                                |

**Fig. 12.14** Application rate curve for two pivot rotations per day with LESA sprinkler and soil infiltration curve for intake family 4 soil

|        | C          | D                  | E    | F            | G         |
|--------|------------|--------------------|------|--------------|-----------|
| m      |            | Sprinkler distance | 400  | m            | Fraction  |
| ha     | Hide graph | Wetted diameter    | 4    | m            | Net app   |
| hr     |            | Rotation rate      | 12   | hrs rotation | net dept  |
| mm/day | Show graph | Sprinkler app time | 1.15 | minutes      | Max app   |
| L/sec  |            | Sprinkler spacing  | 2    | m            | Sprinkler |



that surface storage as 1.2, 0.7, 0.25, and 0 cm for slopes of 0.5, 2, 4, and 4.5 %, respectively.

**Example 12.5** Determine whether the LESA system in Examples 12.2, 12.3 and 12.4 will have ponding and or runoff in an intake family 4 soil with a single rotation per day and with two rotations per day. Surface depressions hold 4 mm/pass. Show the infiltration and sprinkler application curves.

**Single rotation per day**

The sprinkler application and infiltration curve data is generated in in cells D11:D50. Infiltration curves and

sprinkler application curves are shown in Figs. 12.13 and 12.14. The infiltration curve does not include surface storage or the 0.6985 mm in the NRCS equation. However, the calculation of runoff (2.82 mm) in cell B14 (Fig. 12.13) does include the terms.

This example illustrates why LESA systems must rely on surface storage to hold water until infiltration is completed. Even the highest infiltration rate classification (intake family 4) has runoff with the small application diameter.

**Two rotations per day (12 hours per rotation).**

In this case, the application time is half, 1.14 minutes, and the application depth per pass (7.2 mm) is also half of the

**Fig. 12.15** Two passes per day with no instantaneous infiltration and no surface storage results in 3.29 mm runoff

|    | A  | B      | C                                 |
|----|--|--------|-----------------------------------|
| 8  | Surface storage  | 0      | mm                                |
| 9  | Intake family for infiltration functions (write intake family number in cell B7) |        |                                   |
| 10 | Intake family  | 4      | Put intake family to left         |
| 11 | NRCS_a   | 0.4445 | a and b are automatically updated |
| 12 | NRCS_b   | 0.8230 |                                   |
| 13 | Include the initial depth  | FALSE  | This is the 0.6985 mm infiltr     |
| 14 | Runoff   | 3.29   | mm                                |
| 15 | Infiltration + storage   | 4.58   | mm                                |
| 16 | Sprinkler application  | 7.87   | mm                                |

**Fig. 12.16** Single pass per day with instantaneous infiltration TRUE and 4 mm surface storage results in no runoff

|    | A  | B      | C                                 |
|----|--|--------|-----------------------------------|
| 8  | Surface storage  | 4      | mm                                |
| 9  | Intake family for infiltration functions (write intake family number in cell B7) |        |                                   |
| 10 | Intake family  | 4      | Put intake family to left         |
| 11 | NRCS_a   | 0.4445 | a and b are automatically updated |
| 12 | NRCS_b   | 0.8230 |                                   |
| 13 | Include the initial depth  | TRUE   | This is the 0.6985 mm infiltr     |
| 14 | Runoff   | 0.00   | mm                                |
| 15 | Infiltration + storage   | 7.87   | mm                                |
| 16 | Sprinkler application  | 7.87   | mm                                |

single pass application depth. Thus, the maximum application rate is the same as the single pass.

$$\begin{aligned} \frac{di}{dt_{\max}} &= \left(\frac{4}{\pi}\right) \left(\frac{i_a}{T_a}\right) = \left(\frac{4}{\pi}\right) \left(\frac{7.85 \text{ mm}}{1.145 \text{ min}}\right) = 8.74 \text{ mm/min} \\ &= 52 \text{ cm/hr} \end{aligned}$$

$$\begin{aligned} \left(\frac{di}{dt}\right) &= \sqrt{\left(\frac{di}{dt}\right)_{\max}^2 \left(1 - \frac{(t - \tau_a/2)^2}{(\tau_a/2)^2}\right)} \\ &= \sqrt{52^2 \left(1 - \frac{(t - 0.572)^2}{(0.572)^2}\right)} \end{aligned}$$

The *CP\_Infilt\_RO* worksheet is adjusted for this scenario by changing cell E3, as shown in Fig. 12.14.

The depth of runoff without surface storage and instantaneous infiltration (0.6985 mm) is determined by setting cells B10 to zero and cell B13 to FALSE (3.29 mm in Fig. 12.15). However, with a surface storage depth of 4 mm, there is no runoff (Fig. 12.16).

**Example 12.6** Determine the depth of ponding for an impact sprinkler mounted on top of a center pivot irrigating an intake family 4 soil and an intake family 0.2 soil. The wetted diameter is 35 m. The net application

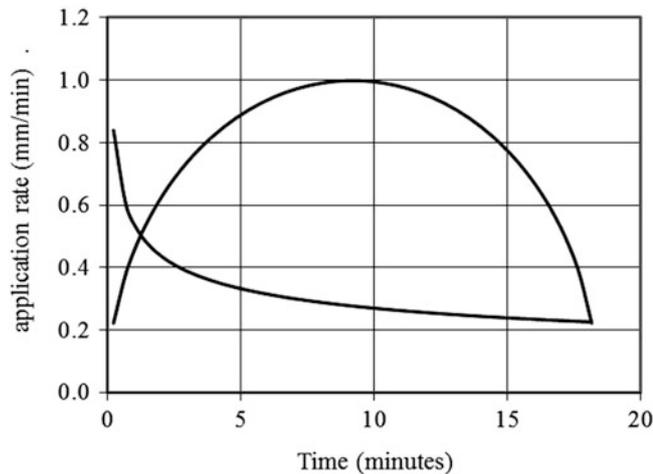
rate,  $i_a$ , is 14.4 mm/pass, and the pivot has a 22 hr rotation cycle. Ignore instantaneous infiltration and the 0.6985 constant in the NRCS calculation of total infiltration. The pivot diameter is 400 m diameter pivot.

$$\begin{aligned} T_a &= T_r \left(\frac{D_w}{2\pi r}\right) = 22 \text{ hr} \left(\frac{35}{2 * \pi * 400}\right) = 0.306 \text{ hr} \\ &= 18.4 \text{ min} \end{aligned}$$

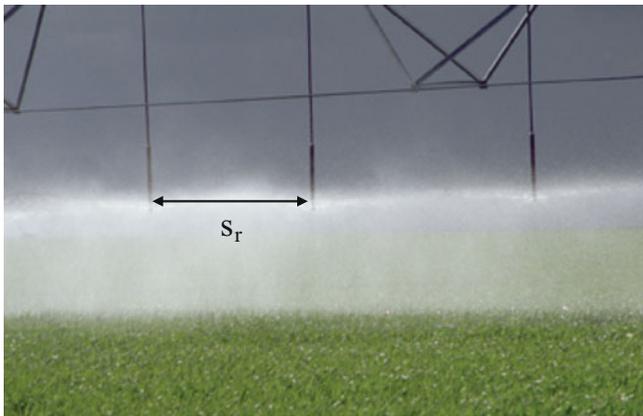
$$\begin{aligned} d_{\max} &= \left(\frac{4}{\pi}\right) \left(\frac{i_a}{T_a}\right) = \left(\frac{4}{\pi}\right) \left(\frac{14.4}{18.4}\right) \\ &= 1.0 \text{ mm/min} \left(\frac{\text{cm}}{10 \text{ mm}}\right) \left(\frac{60 \text{ min}}{1 \text{ hr}}\right) = 6 \text{ cm/hr} \end{aligned}$$

$$\begin{aligned} \left(\frac{di}{dt}\right) &= \sqrt{\left(\frac{di}{dt}\right)_{\max}^2 \left(1 - \frac{(t - \tau_a/2)^2}{(\tau_a/2)^2}\right)} \\ &= \sqrt{6^2 \left(1 - \frac{(t - 9.2)^2}{(9.2)^2}\right)} \end{aligned}$$

There is no ponding with the intake family 4 soil; however, approximately half of the water, 7.1 mm, is ponded on the intake family 0.2 soil (Fig. 12.17).



**Fig. 12.17** Application rate curve and intake family curves for single rotation per day with top mounted impact sprinkler



**Fig. 12.18** Sprinkler spacing

## Center Pivot Sprinkler Spacing and Flow Rate

Sprinkler flow rates and spacing (Fig. 12.18) vary along the center pivot pipeline. Individual sprinkler flow rates are proportional to the ratio of land area irrigated by each sprinkler to the entire pivot flow area.

$$q_r = r(s_r)(2Q_p)/(r_{\max})^2 \quad (12.9)$$

where

$q_r$  = sprinkler flow rate at a radial distance from the pivot point, L/sec.

$s_r$  = distance between sprinklers at radial distance  $r$ , m

$r$  = radial distance from pivot point, m.

**Example 12.7** Sprinkler spacing is 1.5 m. Calculate the flow rate of the middle and last sprinklers for a 400 m center pivot with a 95.3 L/sec flow rate.

$$\begin{aligned} q_{400} &= 400 \text{ m}(1.5 \text{ m})(2)(95.3 \text{ L/sec})/(400 \text{ m})^2 \\ &= 0.71 \text{ L/sec} = 43 \text{ L/min} = 11.3 \text{ gal/min} \end{aligned}$$

The flow rate at the midpoint of the pivot pipeline is calculated as follows.

$$\begin{aligned} q_{200} &= 200 \text{ m}(1.5 \text{ m})(2)(95.3 \text{ L/sec})/(400 \text{ m})^2 \\ &= 0.36 \text{ L/sec} = 21 \text{ L/min} = 5.7 \text{ gal/min} \end{aligned}$$

The  $q_{200}$  flow rate is half of the  $q_{400}$  flow rate: sprinkler flow rates vary linearly along the pipeline because the area covered by each sprinkler is product of spacing and circumference, which are directly proportional to the distance to the center.

Sprinkler spacing and flow rate can be varied along a pivot in order to achieve a relatively uniform application distribution along the pipeline without having extremely large nozzles at the end. For example, the center pivot represented in Fig. 12.19 has sprinkler spacing,  $s_r$ , 5 m, 3 m, and 2 m, in the inner, middle, and outer sections of the pivot, respectively. Intervals are varied near wheels where half-circle sprinklers are used in order to avoid wetting the wheel tracks. Wetting the tracks cause the wheels to sink into the soil. It is difficult to have a uniform application rate near the pivot point (left side of Fig. 12.19) because the relative radius changes quickly. The application rate along the rest of the pivot are relatively uniform (10 % measured CV based on nozzle flow rates).

Pivot manufacturers determine optimal sprinkler flow rates and nozzle sizes with computer programs. Farmers receive a ring of nozzles from manufacturers, and remove the nozzles from the ring one at a time in order to install them in the right order.

Sprinkler flow rate is proportional to the square root of pressure because a sprinkler is an orifice –  $Q = kH^{0.5}$ . If one sprinkler operates at 25 m pressure and another at 20 m pressure, then the pressure ratio is 0.8, but the flow ratio is 0.91.

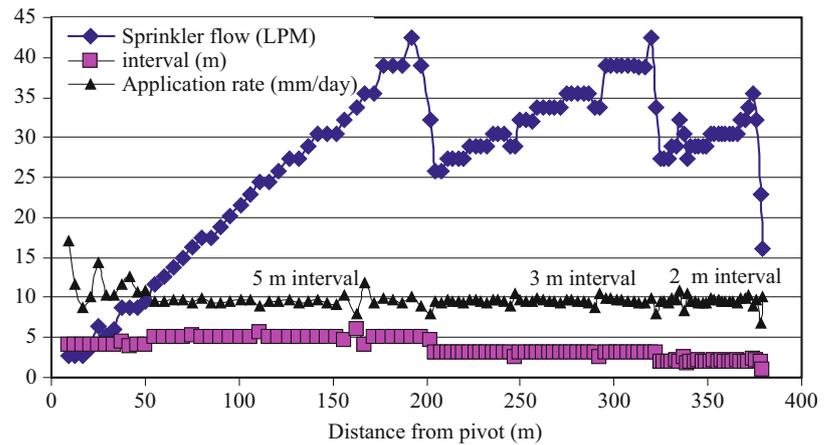
$$Q_2 = Q_1 \sqrt{\frac{H_2}{H_1}} = Q_1 \sqrt{\frac{20}{25}} = 0.91 Q_1$$

Pressure regulators (Fig. 12.20) solve the pressure variation problem; however, they dissipate 5 PSI (35 kPa) pressure so the system pressure requirement is higher. Pressure regulators expand a spring as pressure increases, causing the cross-sectional flow area to decrease. This decreased area increases the pressure drop across the device and maintains the design discharge operation pressure. The 30 PSI (210 kPa) pressure regulator shown in Fig. 12.20 requires 35 PSI (245 kPa) at the pressure regulator inlet.

Center pivots operating on flat ground do not require pressure regulators because the nozzles are designed to operate at the pressure along the pipeline.

Sprinkler flow rate is calculated with a modified orifice equation.

**Fig. 12.19** Sprinkler flow rates, application rate and intervals between sprinklers on center pivot irrigation system



**Fig. 12.20** Pressure regulator (Courtesy of Nelson Irrigation Corporation)

D = nozzle diameter, mm  
 Q = flow rate (LPM).

**Example 12.9** What is the flow rate of a 3.57 mm nozzle (9/64”) at a pressure of 340 kPa (50 PSI)?

$$Q = 0.0666 D^2 H^{0.5} C_d = (0.0666)(3.57^2)(340^{0.5})(0.97) = 15.2 \text{ LPM} = 4 \text{ GPM}$$

If center pivots operate on a landscape with significant elevation change, then pressure regulators are required. The rule of thumb is that if energy fluctuation due to elevation change is greater than 20 % of design pressure, then pressure regulators should be used. Rather than a rule of thumb, engineering economic analysis can determine whether or not to add pressure regulators. Would the increase in uniformity and resultant decrease in water cost be greater than the capital cost of the pressure regulators and the extra cost of energy. This question is evaluated in Example 12.11.

**Example 12.11** Calculate the cost of using pressure regulators to regulate pressure (3.5 m extra pressure) in a center pivot. The evapotranspiration requirement,  $ET_c$ , is 1,200 mm, and the 400 m pivot covers a 50 ha area. The water application efficiency is 85 %, and the pump energy efficiency is 85 %. The cost of energy is \$0.10/kW-hr. Assume a 20 year project life and 6 % required rate of return (ROR).

Depth of water required

$$1,200 \text{ mm} / 0.85 = 1,412 \text{ mm}$$

The increased pressure requirement is 5 PSI = 3.5 m.

Use Eq. 2.16 to calculate the energy per ha

$$E = \frac{0.0272(1,411 \text{ mm})(3.5 \text{ m})}{0.85} = 158 \text{ kW} - \text{hr/ha}$$

Calculate the energy cost per year for the 50 ha area.

$$Q = 29.82 D^2 H^{0.5} C_d \quad (12.10)$$

where

H = pressure, PSI

D = nozzle diameter, in

Q = flow rate (GPM)

$C_d$  = sprinkler nozzle discharge coefficient

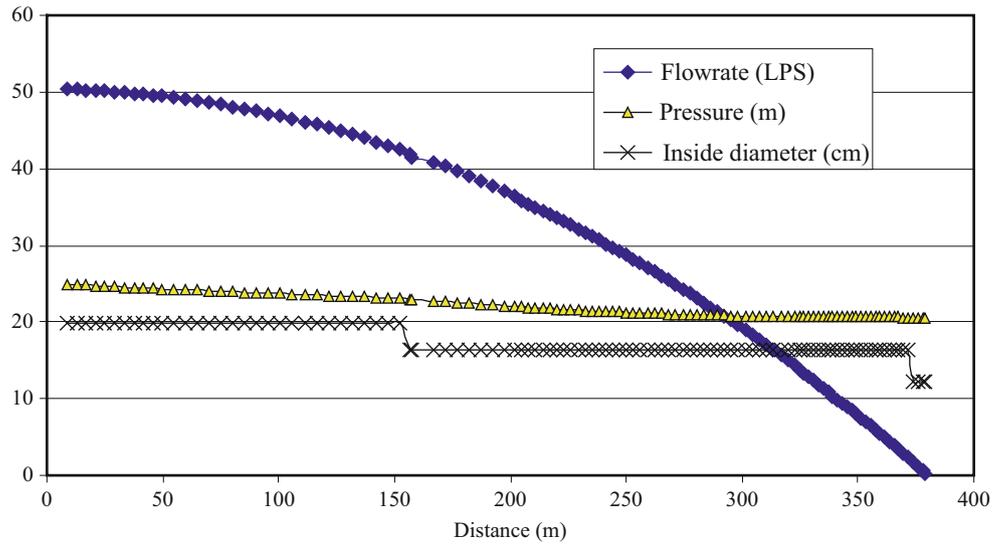
For metric units:

$$Q = 0.0666 D^2 H^{0.5} C_d \quad (12.11)$$

where

H = pressure, kPa

**Fig. 12.21** Pipe flow rate, pressure, and pipe diameter for center pivot



$$(\$ / ha) * 50 \text{ ha} = \left( \frac{158 \text{ kW} - hr}{ha} \right) \left( \frac{\$0.10}{\text{kW} - hr} \right) * 50 \text{ ha}$$

$$= \$790 / year$$

Convert to the present value.

20 year project, 6% ROR, \$790 payment → \$9,061.

If the increased value of yield with uniform application is greater than \$9,061 over the life of the project, the pressure regulators should be used.

**Example 12.10** Calculate the pressure loss along a center pivot irrigation pipeline. Inlet flow rate is 50.3 L/sec, Length is 380 m, and inside diameter of the pipe is 19.79 cm (8 inch pipe) along the entire length of the pipe. The inside surface of the pipe is galvanized steel.

For galvanized steel, assume a C value of 130.

$$H_L = kL \left( \frac{Q}{C} \right)^{1.852} / D^{4.87} = 1.22 * 10^{10} (380 \text{ m}) \left( \frac{50.3}{130} \right)^{1.852} / 198^{4.87}$$

$$= 5.24 \text{ m}$$

$$H_{act} = H_{Lp} F = 5.24 \text{ m} (0.54) = 2.8 \text{ m}$$

As flow decreases along the center pivot, it is possible to reduce pipe diameter. For multiple pipe diameters, the pressure loss must be calculated for each pipe section with a spreadsheet.

The center pivot pipeline represented by Fig. 12.21 has an initial pipe diameter of 19.79 cm ID. Pipe diameter is reduced to 16.3 cm ID (6 inch pipe) at 152 m and to 12.2 cm ID (4 inch pipe) at 374 m where the pipe extended beyond the last tower. The pressure change over the length of this pipeline on a level field is shown in Fig. 12.24. There is minimal pressure drop at the end even though pipe diameter is small. With the multiple pipe diameters, the pressure drops from 25 m at the beginning of the pipeline to 20.6 m at the end of the pipeline, a loss of 4.4 m. The pressure loss would be 2.8 m (Example 12.10) with a single pipe diameter.

### Center Pivot Pipeline Design

Minimizing center pivot pipe diameter reduces pipe and structure cost because the structure must carry the weight of the pipe. However, reducing pipe size increases pressure loss in the pipeline and thus increases the pressure requirement of the pump (increases energy cost).

Center pivot pressure loss can be calculated in a spreadsheet, as demonstrated in Chap. 7. Alternatively, if the entire pipeline has a single diameter, then the Christensen factor (F) for multioutlet pipelines can be used. The Christensen factor for center pivots is 0.54.

$$H_{act} = H_{Lp} F \tag{12.12}$$

where

- $H_{act}$  = actual pressure loss in the multioutlet pipeline, m
- $H_{Lp}$  = pressure loss in a pipeline with no outlets with inlet flow rate, m
- F = Christiansen’s F factor.

### Center Pivot Simulation in Uneven Landscapes

The Chapter 12 Center pivot program calculates sprinkler flow rates and pressures for center pivot movement on an uneven landscape. Sprinkler, pipe, energy, and financial



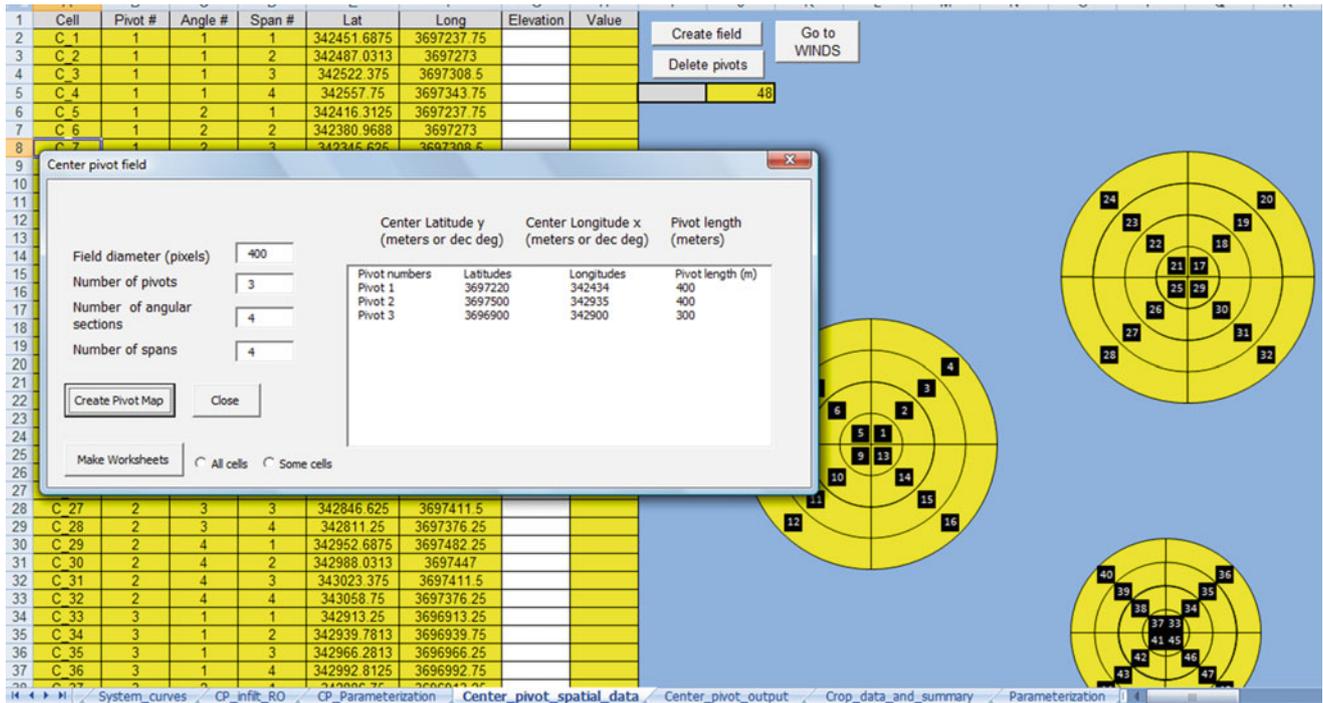


Fig. 12.23 Center\_pivot\_spatial\_data worksheet with three pivots

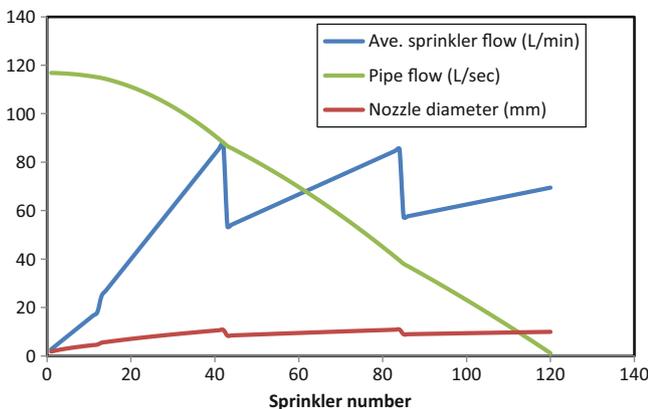


Fig. 12.24 Sprinkler flow rate, pipe flow rate, and nozzle diameter versus distance along pivot

radial position, and latitude and longitude of the centroid. Elevation of the sections are input by the user in column G (white column) of the *Center\_pivot\_spatial\_data* Worksheet. Make sure to write TRUE in cell C6 in the *CP\_Parameterization* worksheet in order to keep the elevations that you entered when the program runs. Cells E2:G20 in the *CP\_Parameterization* worksheet allow the user to specify the locations and lengths of the pivots. In order to allow the user to visualize the locations of the pivots and section locations, the pivots are drawn on the *Center\_pivot\_spatial\_data* worksheet (Fig. 12.23). The locations can

also be changed in the dialog box, which is triggered by the *Create pivot field* button. The upper box in the Form allows the user to specify the dimensions of the worksheet (number of pixels) in the which the pivots are drawn.

The *Center Pivot Seasonal Simulation* button runs a simulation of the selected (cell C9) center pivot. Spatial, flow, and elevation data are written to the *CP\_flow\_output* worksheet. System curves (flow vs. inlet pressure) for the center pivot are written to the *CP\_System\_curves* worksheet. Yield data are written to the *CP\_yield\_output* worksheet. Summary economic data is written to the *CP\_summary\_data* worksheet.

Sprinkler flow rate, nozzle diameter and pipe flow rate (Fig. 12.24), elevation profile of each pipe section (Fig. 12.25), are written to the *CP\_flow\_output* worksheet. Pipe pressure losses are calculated based on pipe flow rates with the Hazen-Williams equation. As in Chap. 7, the calculation begins with the last sprinkler and moves backward toward the first. Sprinkler nozzle diameters are then calculated based on the resultant pipe pressure at each position.

Sprinkler pressures (Fig. 12.26) and flows (Fig. 12.27) in each quadrant are calculated based on elevation and the Hf calculation (friction loss). Flow rates are a function of nozzle diameter and pressure. Figure 12.28 shows relative application rates based on the variable sprinkler flow rates. All values are relative to the lowest application rate, which is at the end of the pivot in quadrant 2, the high point on the field.

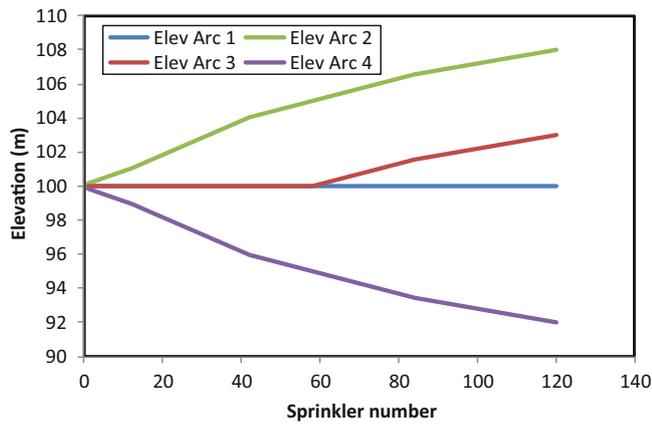


Fig. 12.25 Elevation of each quadrant versus distance along pivot

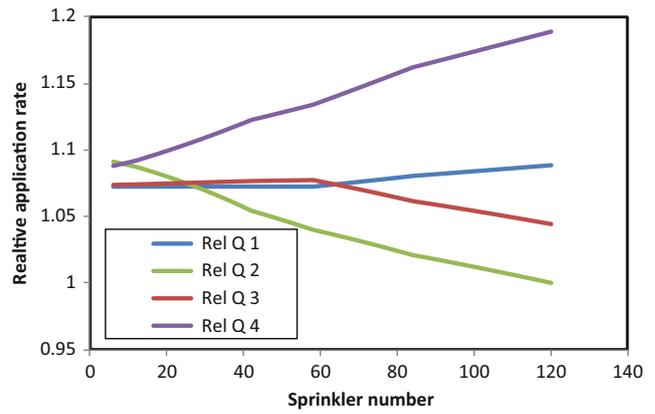


Fig. 12.28 Relative application rates in quadrants along pivot without pressure regulators

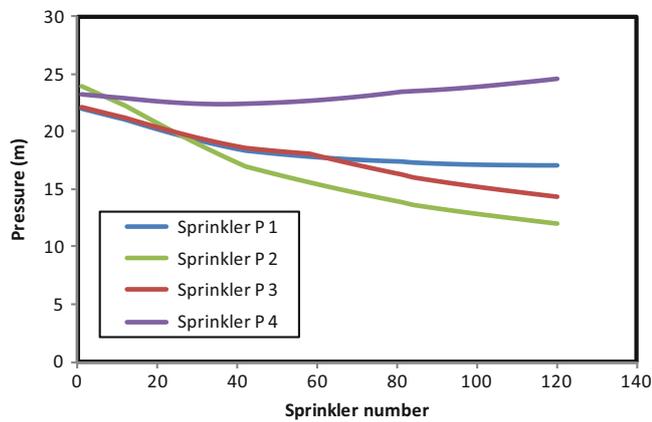


Fig. 12.26 Sprinkler pressures in each quadrant versus distance along pivot

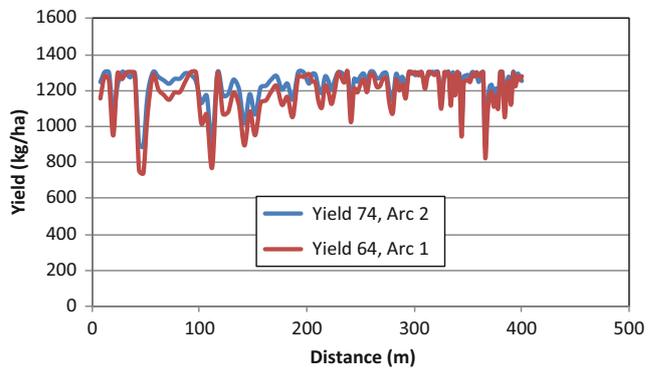


Fig. 12.29 Yields for two different quadrants and average depths

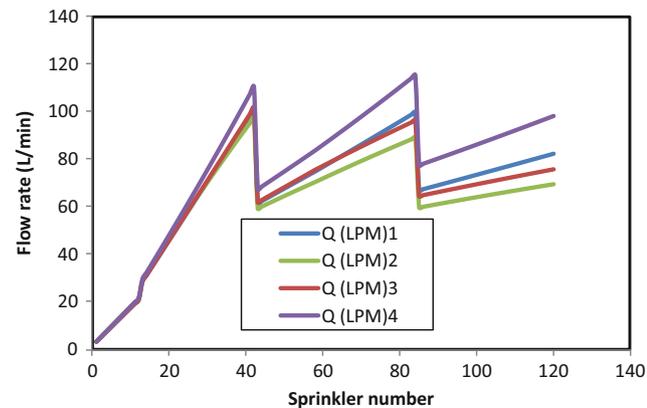


Fig. 12.27 Sprinkler flow rates in each quadrant along the pivot

Quadrant 2 has a lower overall pressure and flow rate than the other quadrants, particularly the downhill quadrant (4) as shown in Fig. 12.26. This is caused by the fact that the pivot

has a system curve, which is the relationship between flow rate and pressure. Greater pressure is required for the uphill quadrant (2) so the overall flow rate goes down. The system curve calculation is conducted in VBA by running the pivot in each quadrant over a range of pressures and then developing pressure-flow rate curves for each quadrant. The minimum pressure along the pipeline is not necessarily at the end of the pipeline. There may be a high point within the field that has a low pressure. The program finds the minimum pressure as a function of inlet pressure.

Spatial variability (CV in cell F26 in *CP\_Parameterization* worksheet) is evaluated for the application depths specified in cells F27 and F28 in *CP\_Parameterization* worksheet. Applied water depths and yield output (Fig. 12.29) data are written to the *CP\_yield\_output* worksheet for each average depth applied and each quadrant. Finally, an economic summary of all evaluated depths is written to the *CP\_summary data* worksheet

## Center Pivot Pump and Pipe Network Design

Center pivot farms are often supplied by a central reservoir and pump station (Fig. 12.30).

The pump station should be designed to supply water flow rates that range from the water requirement for one pivot to all of the pivots on a farm. Although wells can be drilled at each pivot point, flexibility of operation and maintenance is gained when wells are networked into a central reservoir, which then supplies water to all pivots. Use of a reservoir also provides some protection against temporary water supply failures from the canal district or individual wells. A set of centrifugal pumps is connected to a single manifold. The manifold then feeds a set of stainless steel screen filters. The filters are connected to a second manifold that feeds the pipe network that supplies all of the pivots on the farm. In this way, any pump or any screen can be shut down and repaired or cleaned while the others are running.

The pump pressure requirement is the sum of the following:

- Required sprinkler pressure
- Required pressure drop across the pressure regulator,
- Pipe friction loss from one end of the pivot to the other,
- Elevation difference between the ground surface and the sprinklers,
- Elevation difference between the pumping water surface and the maximum elevation in the field,
- Friction loss in the supply pipe network,

- Pressure loss in filters
- Friction losses in fittings and valves.

**Example 12.12** Design a pump station for the pivot farm shown in Fig. 12.31. The maximum elevation in the center pivot irrigated fields 1, 2, 3, and 4 are 10 m, 4 m, 6 m, and 8 m higher than the reservoir, respectively. Pipe friction in the N-S pivot submains is 2 m, and pipe friction in the EW mainline is 4 m to the midpoint and 3 m from the midpoint to the end. Each pivot requires 95 LPS

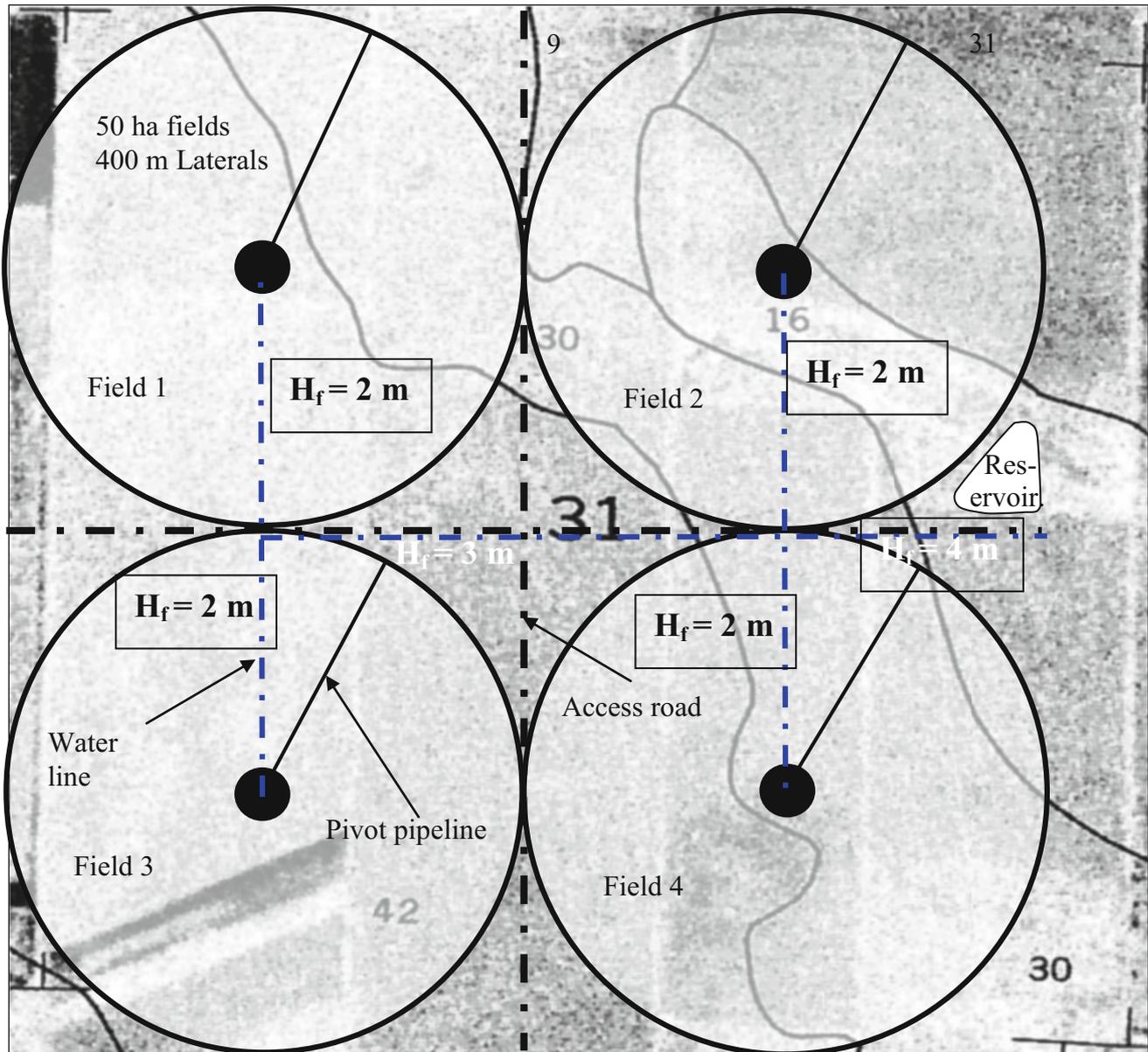
Use 4 pumps so that 1–4 pivots can be run at any time. Field 1 is the worst case; thus, design all pumps to supply the correct pressure to pivot 1. You can't connect pumps with different discharge pressures to the same manifold.

- +15 m – sprinkler pressure (20 PSI)
- +3.5 m – pressure regulator required pressure difference between pipe and operating pressure
- +2.8 m – pipe friction loss in center pivot
- +2 m – elevation of sprinklers above ground surface.
- +10 m – elevation difference between highest point in field and reservoir surface
- +2 + 3 + 4 m – Pipe network
- +3 m – friction loss in stainless steel screen filter
- +5 m – friction loss in valves and fittings (check valve, manifold, pump suction).
- 49m – total pressure required.

Each of the 4 pumps should provide 49 m pressure at 95 LPS.

**Fig. 12.30** Reservoir and pump station for center pivot farm. Cylindrical stainless steel ring filters and manifold in foreground. Motors on top of turbine pumps are seen behind manifold (Credit Paul Colaizzi, University of Arizona and USDA-ARS Bushland, Texas)





**Fig. 12.31** Center pivot layout on a typical section of land (1 mile by 1 mile) with pipe friction losses for Example 12.10

**Questions**

1. Discuss the different types of sprinkler nozzles and systems used on center pivots. Discuss the strengths and weakness of the systems.
2. What is the difference between a linear move and a center pivot irrigation system?
3. Calculate the percent evaporation from sprinkler droplets for the parameters in Example 12.1 except that relative humidity is 50 %. If the application depth is 25 mm to a mature corn crop from overhead impact

- sprinklers, then what is the total depth of evaporation + canopy interception loss?
4. Calculate the percent evaporation from overhead sprinklers for the parameters in Example 12.1 except that relative humidity is 60 %. What is the depth of evaporation for an application depth of 25 mm to a mature corn crop from overhead impact sprinklers? Consider canopy interception and droplet evaporation?
5. Calculate the flow rate of a center pivot that has a length of 350 m, and gross application depth 15 mm/day. The pivot operates for 21 hours/day.
6. Calculate the maximum application rate for the parameters in question 12.5. The sprinkler wetted

- diameter is 4 m and the percent evaporation is 14 %. Then, show that the maximum application rate is the same if the pivot rotates three times per day (7 hour rotation). Show calculation and explain why the maximum application rate is the same in both cases.
7. Using the parameters in question 12.6, calculate the depth of runoff and maximum application rate during each pass for an intake family 3 soil with 2 mm surface storage. Include the 0.6985 initial infiltration depth. Calculate for three revolutions per day. The percent evaporation is 14 %. Use *Chapter 12 Center pivot* program and hand calculations.
  8. Repeat Question 12.7, but change to one rotation per day.
  9. Calculate the flow rate and runoff at the middle sprinkler (175 m from pivot point) for the pivot described in questions 12.6–12.9 for a single 21 hour rotation per day. Sprinkler spacing is 2 m at the middle of the center pivot. Fraction evaporation is 14 %. Sprinkler wetted diameter is 3.5 m. The soil intake family is 1. Surface storage is 4 mm.
  10. Derive the Christensen's F factor in Eq. 12.12 by assuming that a center pivot has four sprinklers (1/4, 1/2, 3/4, and full length down the pivot).
  11. Low-pressure sprinkler nozzles at Paradise Cattle Company have a wetted diameter ( $D_w$ ) of 2 m. The average rotation period of the center pivot is 8 hours. The pivot is 400 m radius and the flow rate is 95 L/sec. 5 % of water is lost to evaporation. Calculate the daily gross application rate, and plot the instantaneous application rate as a function of time at the 400 m. The Paradise Cattle Company pivots used in this and the next problem are described in the *Center pivot pump and pipe network design* section.
  12. Plot the instantaneous application rate vs. time for at 200 m for the same parameters as in question 12.11.
  13. Calculate the pressure loss in a center pivot that has a length of 350 m, and gross application depth applied during each pass is 5 mm. Time of rotation is 8 hours. Use 198 mm pipe. There is no down time.
  14. A sprinkler has a flow rate of 5 GPM at 20 PSI. What is the flow rate at 25 PSI?
  15. Use the *Chap. 12 Center pivot* model to find the optimal water application depth for CV values of 0.1 and 0.3.
  16. Is it worth adding pressure regulators for the elevations shown in Fig. 12.23? Regulators cost is \$5.00 per. This is the same as question 12.15, but add the regulators.
  17. A center pivot irrigation system requires 200 kPa sprinkler pressure. There are five pivots each with a flow rate of 110 L/sec. Pressure regulators are used. Sprinklers are 1 m above the land surface. There is a 4 m pressure loss in the pivot pipeline, and 10 m head loss in the pipe network between the pumps and the worst case pivot. The maximum elevation of the land surface is 20 m higher than the reservoir. Make all other necessary assumptions. How many pumps are required? At what pressure and flow rate should the pumps operate?