14 Agricultural Sprinkler Irrigation

Agricultural sprinkler systems include wheel-lines, hand-lines, undertree sprinklers, and microsprinklers. The design process includes selecting an appropriate sprinkler and sprinkler spacing, calculating the number and dimensions of zones, designing the pipe network, and selecting the pump. Constraints such as orchard tree spacing and premanufactured aluminum pipe lengths often limit the spacing options. Sources of nonuniformity in agricultural sprinkler systems include variability of application rates within a sprinkler wetted area and hydraulic variation of lateral pressure. Although not normally part of the design process, this chapter shows how to describe the variability of wheel-line application depth based on pressure variation and sprinkler application pattern. The instructor may decide not to include these details. An economic/environmental model is presented that optimizes seasonal application depth with respect to yield, energy and water cost, and environmental contamination.

If possible, laterals should be oriented in the downhill direction, even if that means bringing a mainline up to the top of the hill Pipe sizes are selected with the goal of maintaining uniform discharge pressure and flow rate throughout the sprinkler system. In this case, the slope of the field is an advantage, and pipes are selected such that friction energy loss and elevation pressure gain offset each other. In this way, uniform pressure is maintained along the pipe. For this reason, it is generally worthwhile, even if the water source is at the bottom of the field, to pipe the water to the top of the field and then run laterals and/or submains in the downhill direction.

Water hammer is not a hazard for sprinkler system laterals and submains because every lateral/sprinkler acts as an air vent/pressure relief valve. Thus, the 1.5 m/sec rule may be relaxed in order to meet the more important goal of maintaining uniform pressure along the laterals. This does not apply to the mainline because it is blocked from the sprinklers by a valve.

Because flow decreases with distance, sprinkler laterals generally have smaller pipes at the end and larger pipes near the inlet. The process of designing the laterals begins at the last sprinkler. The minimum acceptable pressure is assigned to the last sprinkler on the lateral. Then, the pressure loss or gain between the last and previous sprinkler is calculated. Next, the flow at the previous sprinkler is calculated and the process continues. The pressure at the previous sprinkler is calculated with the following equation.

$$H_{n-1} = H_n + H_L + (s_L)(S/100) \tag{14.1}$$

where

H_n = pressure at the nth sprinkler, m
H_{n-1} = pressure at previous sprinkler, m
H_L = friction loss in pipe, m
s_L = spacing between sprinklers along lateral, m
S = slope, negative for inlet higher than distal end, m/m.

Wheel-Lines

Wheel-lines (also known as wheelmove, sideroll, or lateral-roll) are generally used to irrigate pastures or hay in regions where farms are not large enough for center pivot irrigation systems. Many of these farms are in the northwest United States. For example, 336,000 out of 1.3 million irrigated acres in Utah are irrigated with wheel-lines (Hill 2000). Wheel lines are often used on 40-acre fields (¼ mile by ¼ mile, 1,300 m × 1,300 m), but they are also used on smaller fields.

Wheel-lines are classified as move-and-set or periodic-move irrigation systems. The farmer moves the lateral once or twice a day and allows the system to irrigate for 12 or 24 hours before it is moved to the next position. Wheel-lines have a labor advantage over hand-lines because the

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Fig. 14.1 Wheel-line (Credit NRCS)

wheel-line movement is powered by a small (~2 HP) air-cooled engine (Fig. 14.1). The engine turns the entire pipeline and wheels. The farmer disconnects the wheel-line from the mainline hydrant, turns on the motor to move the wheel-line, and then reconnects the wheel-line to the mainline at the next hydrant. This process takes 20 to 30 minutes. Wheel-lines movement requires much less labor than hand-lines where each pipe is moved by hand to the next position. However, moving hand-lines is a good means of character formation for teenagers who must get up each morning before school and carry hand-lines through a wet field for a few hours.

Hydrants are attached to a mainline that runs along one side of the field (Fig. 14.2). The mainline for wheel-line systems is generally buried PVC plastic pipe with hydrants on vertical pipes sticking out of the ground. However, the mainline can also be constructed from temporary aluminum pipe sections that lay on the ground surface. The mainline is often placed along a fence line for protection. In Fig. 14.3, a mainline runs down the center of two fields (along the fence line) with wheel-lines or hand-lines running in fields along either side.

Handlines are often used to germinate crops. In this case, hand-lines are connected to all hydrants, and water is applied to the entire field several times per day (Fig. 14.4).

Hand-lines can be rotated around a mainline (Fig. 14.2) such that the driest area is always irrigated next. However, wheel-lines cannot be moved from one side of the mainline

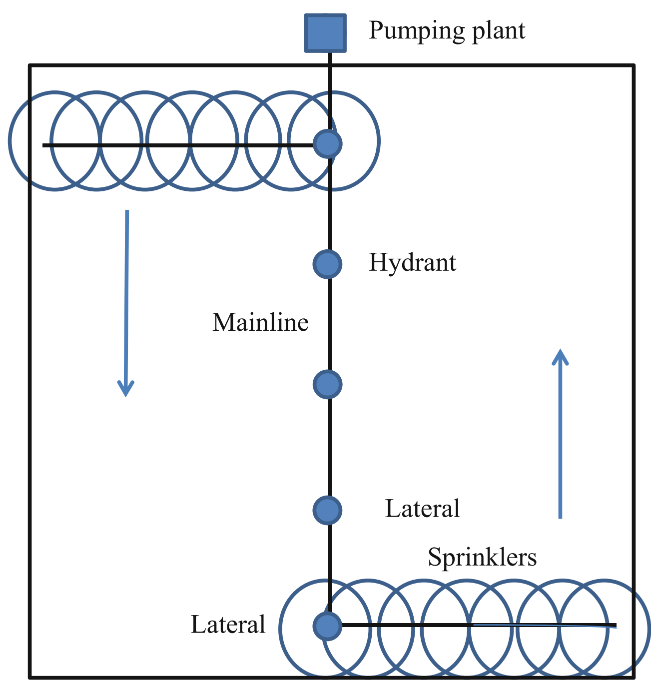

Fig. 14.2 Wheel-line or hand-line field layout (Credit NRCS)

to the other. Thus, when wheel-lines reach the end of the field, they are moved back to the other end of the field and started over in the same direction. Sometimes farmers choose to irrigate in both directions but this may lead to

Fig. 14.3 Wheel-line or hand-line hydrant (Credit NRCS)

Fig. 14.4 Handlines used to germinate lettuce (Credit NRCS)

excessive leaching if the soil profile is already filled by the recent. An assessment of the water-holding capacity of the soil can be made to determine if this is an acceptable practice. One technique used to lessen the effect of moving back to the beginning of the field is to skip every other hydrant in each direction (Hill 2000).

Where wheel-lines and hand-lines are popular the northwest United States, the typical evaporation rate is 0.3 inches (8 mm) per day for pasture or alfalfa irrigation (Fig. 14.2). Wheel-line sprinklers are generally brass impact sprinklers on self-leveling risers (Fig. 14.2) with a 5/32″ (3.97 mm) nozzles operating at 50 PSI (345 kPa). They typically have 40 ft (12.2 m) spacing between sprinklers on the lateral and 60 ft (18.3 m) spacing between hydrants on the mainline. The wetted radius of a 5/32″ nozzle at 50 PSI (345 kPa) is 45 ft (13.7 m). The flow rate can be calculated with Eq. 12.22

$$Q = 0.0666\, D^2 H^{0.5} C_d = 0.0666\; 3.97^2\; 345^{0.5} (0.97) = 18.9\ \mathrm{L/min} = 5.0\ \mathrm{GPM}.$$

In order to prevent water runoff, the steady-state infiltration rate must not be exceeded by the application rate. Wheel-lines can be modeled as a line source irrigation system. If the sprinklers have a wedge-shaped application pattern and there is head-to-head spacing, then the wheel-line as a whole has a wedge shaped application pattern with a peak over the wheel-line. One can calculate the maximum application rate with an analytical equation. For a wedge-shaped application pattern, the application rate at any distance from the sprinkler is calculated by interpolation where di/dt_{max} is the peak application rate at the sprinkler.

$$\left(\frac{di}{dt}\right) = \left(\frac{di}{dt}\right)_{max} \left(\frac{r_{max} - r}{r_{max}}\right) \tag{14.2}$$

where

r_{max} = maximum wetted radius, m
r = distance from sprinkler, m.

The sprinkler flow rate, Q, is equal to the summation of the product of all application rates and incremental areas.

$$\begin{aligned} Q = \sum \left(\frac{di}{dt}\right)_n A_n = \int_0^{2\pi} \int_0^{rmax} \left(\frac{di}{dt}\right)_{max} \left(\frac{r_{max} - r}{r_{max}}\right) \\ r\ dr\ d\theta = \frac{\pi}{3}\, r_{max}^2 \left(\frac{di}{dt}\right)_{max} \\ \left(\frac{di}{dt}\right)_{max} = \frac{Q}{\frac{\pi}{3}\, r_{max}^2} \end{aligned} \tag{14.3}$$

Thus, for a 5/32″ nozzle with perfect wedge-shaped application pattern, the maximum application rate at the sprinkler is

$$\left(\frac{di}{dt}\right)_{max} = \frac{1.135\ m^3/hr}{\frac{\pi}{3}\,(13.7)^2} = 0.00576\ m/hr = 5.76\ mm/hr$$

The application rate vs. distance from the sprinkler for a wedge-shaped application pattern is the straight line shown in Fig. 14.5. Actual sprinklers do not have a perfect wedge pattern, but something closer to the other pattern shown in Fig. 14.5.

The line source application rate is also a function of the sprinkler overlap. For a wedge shaped application pattern, the application rate at the sprinkler is the sum of the application rate of the sprinkler and the sprinklers on both sides.

$$\begin{aligned} \left(\frac{di}{dt}\right) &= \left(\frac{di}{dt}\right)_{max} + 2\left(\frac{di}{dt}\right)_{max}\left(\frac{r_{max} - s_L}{r_{max}}\right) \\ &= \left(\frac{di}{dt}\right)_{max}\left(1 + 2\left(\frac{r_{max} - s_L}{r_{max}}\right)\right) \end{aligned} \tag{14.4}$$

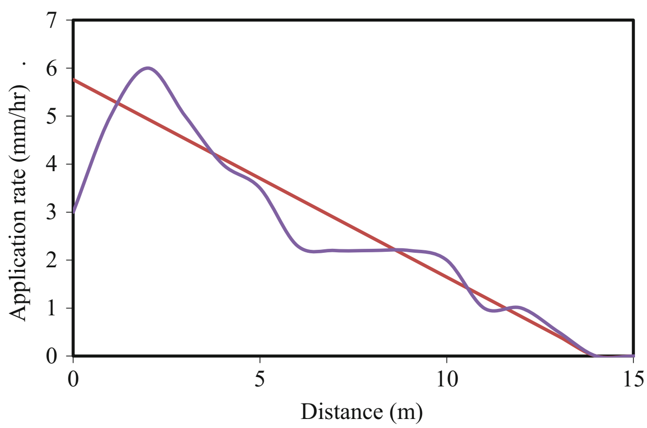

Fig. 14.5 Perfect wedge-shaped pattern and a typical sprinkler distribution pattern

For example, the sprinklers in this example have a 13.7 m application radius, but the sprinklers are only spaced 12.2 m apart. The application rate at the sprinkler is calculated as follows.

$$\left(\frac{di}{dt}\right) = \left(\frac{di}{dt}\right)_{\max}\left(1 + 2\left(\frac{r_{\max} - s_L}{r_{\max}}\right)\right)$$
$$= 5.76\left(1 + 2\left(\frac{13.7 - 12}{13.7}\right)\right) = 7.2 \ mm/hr$$

Application patterns are shown in Fig. 14.6 (from *Sprinkler Uniformity* program), with a peak application rate at the wheel-line and lower application rate between wheel-line positions. For a typical sprinkler pattern such as than shown in Fig. 14.5, with a dip near the sprinkler, some overlap is preferable because it fills in the dip near the sprinkler. This is seen in Fig. 14.6 where the application pattern directly over the wheel-line transect for the typical sprinkler (right side) is actually quite uniform.

With the normal wheel-line spacing and sprinkler nozzle, as long as the soil steady-state infiltration rate is greater than 7.2 mm/hr (0.3 in/hr), then the 5.0 GPM nozzle with wedge-shaped application pattern at 40 ft spacing is acceptable. This would correspond with the 0.3 intake family soil. It is not appropriate to rely on surface storage with wheel-lines because wheel-lines irrigate in the same position for 24 hours. In addition, many wheel-lines are placed in hilly fields so runoff is more likely than in a flat field. In Fig. 14.6, both patterns have a low application rate in the middle between laterals. The CUs for the two sprinkler patterns at 40 ft by 60 ft spacing (Fig. 14.6) are in the range of 80 %. Windy conditions would decrease the CU because droplets would not reach the midpoint between wheel-line positions. Studies at Utah State showed an average 62 % uniformity on 40 ft by 60 ft spacing. For this reason, wheel-line positions are staggered such that the wheel-line is offset to one side of the hydrant during one cycle and to the other side of the hydrant on a next cycle through the field (Fig. 14.7). This results in a 40 ft by 30 ft spacing and much higher CU (Fig. 14.8). Studies at Utah State showed 87 % uniformity for the staggered spacing.

Wheel-lines are constructed from 4″ (3.856 in or 97.9 mm ID) or 5″ (4.844 in or 123.0 mm ID) thick-wall (H-26) aluminum irrigation pipe. Five-inch pipe may be required for the first sections of long wheel-lines or on wheel-lines with high flow rate sprinklers in order to reduce friction loss and maintain pressure uniformity along the wheel-line. The larger pipe can provide higher torque for moving wheel-lines up hills.

Example 14.1 Design (select pipe size) a ¼-mile longwheel-line that has a 1 % downward slope from the inlet to the distal end. Use 5/32″ nozzles with sprinklers on 40 ft spacing. Use sample calculations for the first few sprinklers. Subsequently, evaluate the sprinkler application variability.

Derive an equation for sprinkler flow rate vs. pressure.

$$\mathrm{Q} = 0.0666\ \mathrm{D^2 H^{0.5} C_d} = 0.0666\left(3.97^2\right)\left(\mathrm{H}^{0.5}\right)(0.97).$$
$$\mathrm{Q(L/min)} = 1.018\ \mathrm{H^{0.5}(kPa)}$$

Try the smaller diameter, 4″ (97.9 mm ID) pipe, in order to burn pressure to compensate for energy gained by elevation loss.

Set the last sprinkler at the minimum design pressure of 345 kPa (50 PSI) and calculate flow rate.

$$\mathrm{Q} = 1.018(345)^{0.5} = 18.9\ \mathrm{L/min}$$

Calculate pressure loss in the pipe between the last sprinkler and the next to last sprinkler. The Hazen-Williams C-value for aluminum irrigation pipe is 130.

$$H_L = 1.22{*}10^{10}{*}12.2\ \ m\left(\left(\frac{18.9/60}{130}\right)^{1.852}/97.9^{4.87}\right)$$
$$= 0.00043\ \ m$$

Calculate pressure at the next to last sprinkler with Eq. 14.1.

$$\begin{aligned} & 345\ \mathrm{kPa}/9.8 = 35.2\ \mathrm{m} \\ \mathrm{H_{n-1}} &= \mathrm{H_n} + \mathrm{H_L} + (\mathrm{s_L})(\mathrm{S}/100) \\ &= 35.2 + 0.00043 + 12.2(-0.01) \\ &= 35.08\,\mathrm{m} = 343.8\,\mathrm{kPa} \end{aligned}$$

Calculate flow at the next to last sprinkler

$$\mathrm{Q} = 1.018(343.8)^{0.5} = 18.88\ \mathrm{L/min}$$

Flow in the pipe leading to the next to last sprinkler is

$$\mathrm{Q_{pipe}} = \mathrm{Q_{n-1}} + \mathrm{Q_n} = 18.88 + 18.9 = 37.8\ \mathrm{L/min}.$$

This process continues until the pressures in all sprinklers are calculated (Fig. 14.9). The calculations are made in the *Wheel-line* worksheet (Fig. 14.10).

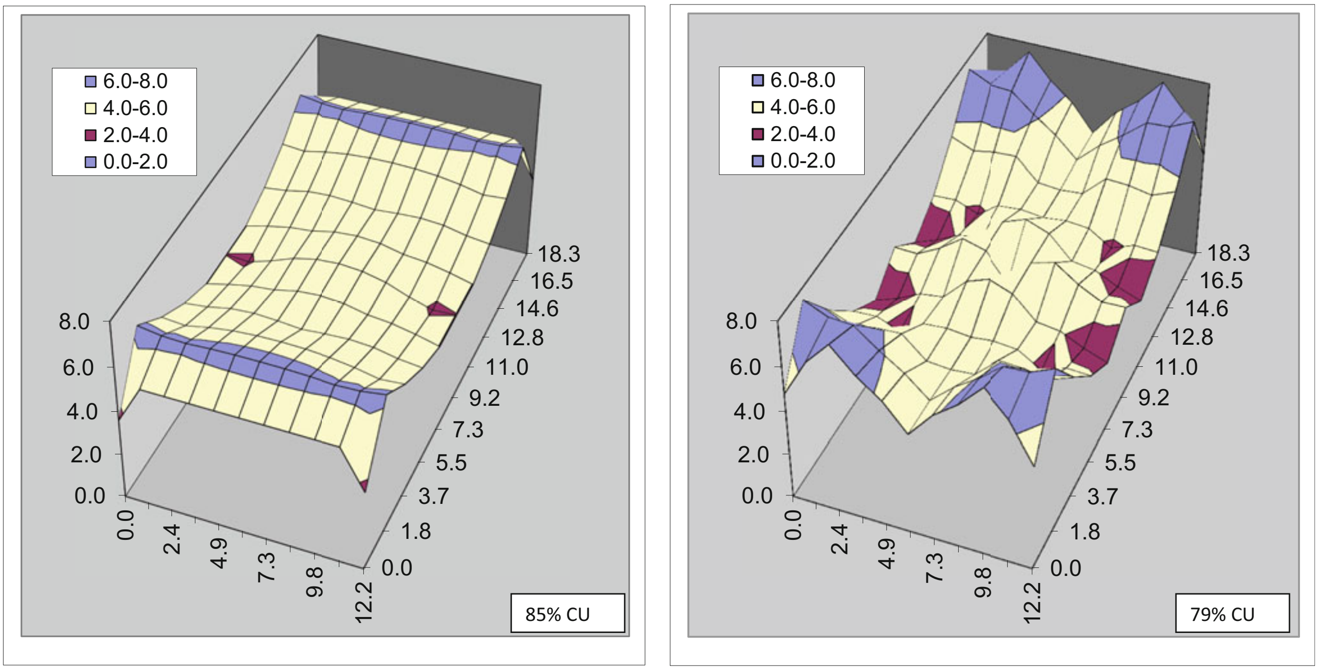

Fig. 14.6 Uniformities for 5/32″ nozzle on 40 ft × 60 f. spacing (12.2 × 18.3) with perfect wedge shape application pattern (*left*) and typical application pattern (*right*)

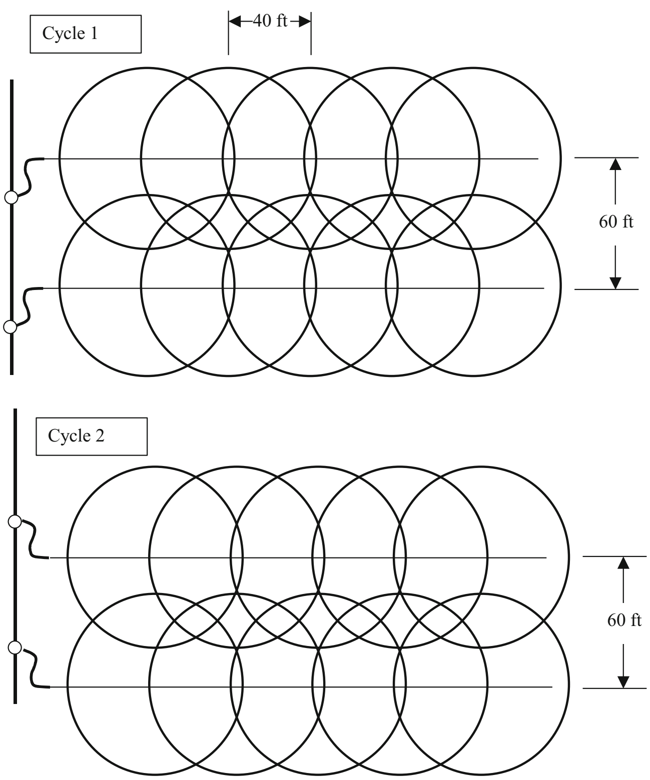

Fig. 14.7 Staggered wheel-line sets

Because of the downhill slope on the wheel-line, the maximum percent difference in flow is less than 3 % (Fig. 14.10). The energy loss due to friction becomes greater than the energy gain due to elevation over the first 120 m of the lateral. However, it is not worth switching to larger pipe in order to reduce friction loss because the pressure at the end of the pipe is greater than the inlet pressure with the 4″ (97.9 mm) pipe.

Unlike the simulation in Chap. 7, sprinkler application rates are generally not normally distributed. It is preferable to calculate the application distribution of a sprinkler zone by using the actual sprinkler application distribution (Fig. 14.8) and the hydraulic variation in sprinkler pressure (Fig. 14.9) or flow rate. In order to do this, relative application rates at all sections of the zone are calculated. In this case, the minimum sprinkler flow rate (18.47 LPM at sprinkler 11 in Fig. 14.10) is designated as the reference flow rate, 1.0 (cell J29 in Fig. 14.10). The field position (Row 0, column 6 in the middle of the right side of Fig. 14.6) minimum application rate is designated as the reference application rate, 1.0. Thus, the minimum application rate in the field is found at sprinkler 11, row 0, column 6. The application rate for any other position is the product of the ratio of sprinkler flow rate to minimum sprinkler flow rate and the ratio of application rate to minimum application rate.

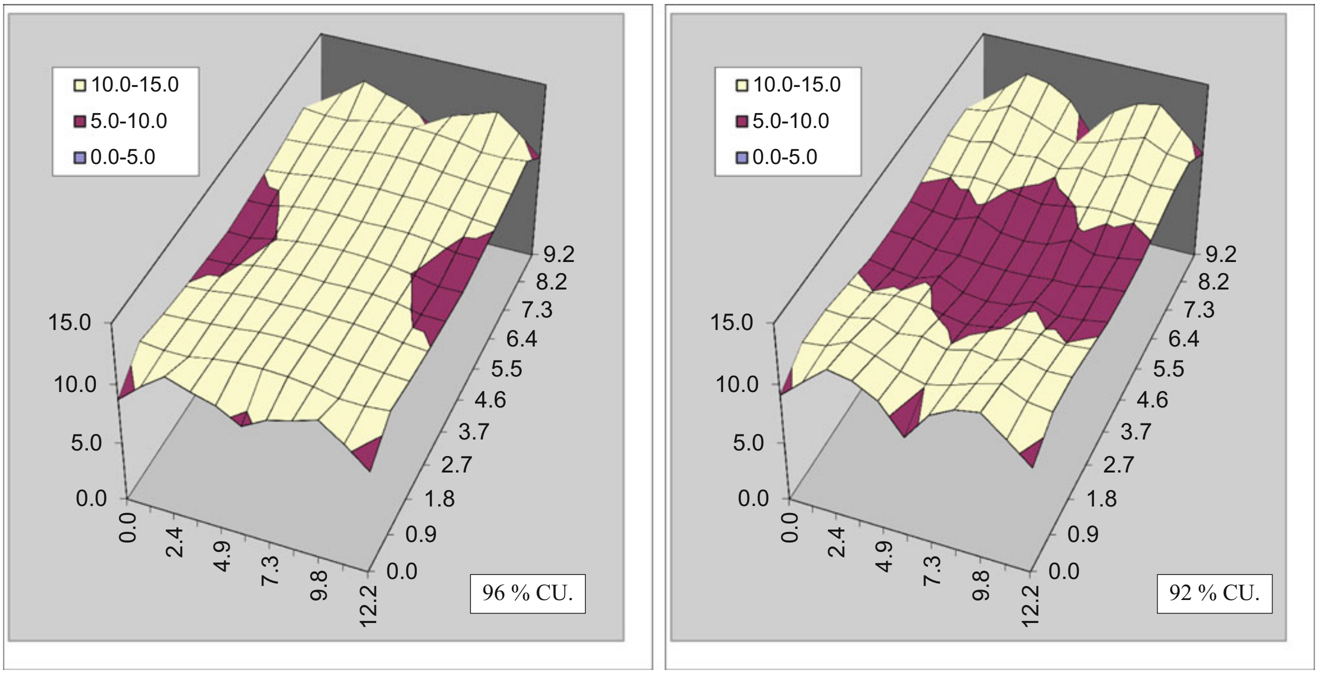

Fig. 14.8 Uniformities for 5/32″ nozzle on 40 ft × 30 f. spacing with perfect wedge shape application pattern (*left*) and typical application pattern (*right*)

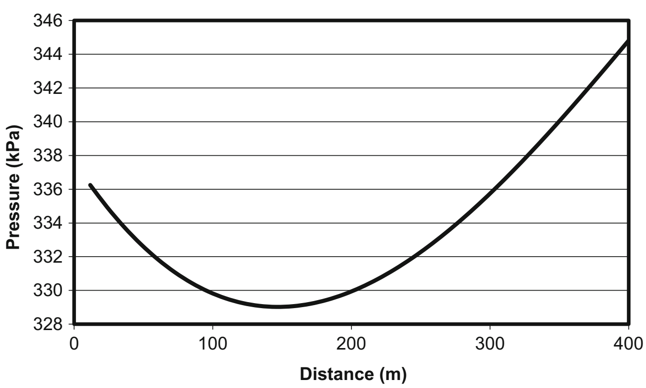

Fig. 14.9 Sprinkler pressures for quarter mile wheel-line with 5/32″ nozzles on 1 % downward slope with 4″ inch pipe

$$\mathrm{Re}l_{j,k} = \left(\frac{Q_j}{Q_{\min}}\right)\left(\frac{\frac{di}{dtk}}{\frac{di}{dt\min}}\right) \tag{14.5}$$

The next step is to find the seasonal application depths at all positions in the zone ($AW_{j,k}$). The average gross application depth ($AW_{ave\text{-}g}$) is the total flow to the zone (cell I5 in Fig. 14.10) divided by the field area and multiplied by the seasonal irrigation time. The average net application depth is the average gross application depth minus evaporated water. The average relative application rate (Rel_{ave}) is found by summing all relative application rates ($Rel_{j,k}$) and dividing by the number of field positions. The application rate at any field position is then found with the following equation.

$$AW_{j,k} = \frac{\mathrm{Re}l_{j,k}}{\mathrm{Re}l_{ave}}\left(AW_{ave-g}\right)\ (1 - L_e) \tag{14.6}$$

where

$AW_{j,k}$ = net depth of water application at position j, k, cm
$\overline{Q}_{\min}$ = minimum sprinkler flow rate, L/min
$\overline{Q}_j$ = sprinkler flow rate at position j, L/h
AW_{ave-g} = average gross application depth, cm
j = sprinkler position
k = position in sprinkler area grid (Fig. 14.7)
$Rel_{j,k}$ = relative depth of application, $(di/dt)_{j,k}$ / $(di/dt)_{min}$.
Rel_{ave} = average of relative depths of application
L_e = fraction evaporation

The program calculates the yield and environmental costs are calculated at each field position based on the applied water at each position. The program begins by calculating the relative application rates for each 10 × 10 sprinkler grid associated with each of the 33 sprinklers on the wheel-line. In this example, there are a total of 3,300 application rates. For example, the depth of application at the 11th sprinkler (cell J30 in Fig. 14.10), 2.4 m Row, 0 m Head location (Fig. 14.3) is 1.47.

$$\mathrm{Re}l_{11,(2..4,0)} = \left(\frac{Q_{11}}{Q_{\min}}\right)\left(\frac{\frac{di}{dt(2.4,0)}}{\frac{di}{dt\min}}\right) = (1.0153)\ (1.45)$$
$$= 1.47$$

	A	B	C	D	E	F	G	H	I	J	K	L
1	Offset	K	1.018	Kpa LPM	Kh	1.22E+10	coefficent	Diameters	97.9	4-inch	Pipe length	402.00
2	TRUE	x	0.5		Slope	-0.01	m/m	(mm) ID	123.0	5-inch		
3	Inlet Pr.	End Press	345	Kpa	CV	9%	sd/mean	Extra Press.	40	kPa	Hide flow graph	
4	336.25	Spr. Spac	12.20	m	C	130	H-W	Pump eff.	70%		Show flow graph	
5		Hyd. Spac	18.3	m	Evap	10	%	Total flow	613.84	LPM	Hide pressure graph	
6											Show pressure	
7	Sprinkler	Distance	Pressure (m)	Pressure (kPa)	Flow (LPM)	Diameter (mm)	Pipe flow (LPM)	Fric loss (m)	% diff flow	Rel	CV simulation	Z-dist
8	33	402.0	35.20	345.00	18.91	97.90	18.91	0.00043	0.00%	1.0239859	19.7556306	0.510262
9	32	389.8	35.08	343.81	18.88	97.90	37.78	0.00155	-0.17%	1.0222163	21.0360407	1.303451
10	31	377.6	34.96	342.63	18.84	97.90	56.63	0.00328	-0.34%	1.02046	17.432146	-0.85301
11	30	365.4	34.84	341.46	18.81	97.90	75.44	0.00558	-0.51%	1.018726	19.5702553	0.459466
12	29	353.2	34.73	340.32	18.78	97.90	94.22	0.00842	-0.68%	1.0170227	16.9651879	-1.10059
13	28	341.0	34.61	339.21	18.75							
14	27	328.8	34.50	338.13	18.72							
15	26	316.6	34.40	337.09	18.69							
16	25	304.4	34.29	336.09	18.66							
17	24	292.2	34.20	335.14	18.64							
18	23	280.0	34.11	334.24	18.61							
19	22	267.8	34.02	333.39	18.59							
20	21	255.6	33.94	332.61	18.57							
21	20	243.4	33.87	331.90	18.55							
22	19	231.2	33.80	331.25	18.53							
23	18	219.0	33.74	330.68	18.51							
24	17	206.8	33.69	330.18	18.50							
25	16	194.6	33.65	329.77	18.49							
26	15	182.4	33.62	329.44	18.48							
27	14	170.2	33.59	329.21	18.47							
28	13	158.0	33.58	329.07	18.47							
29	12	145.8	33.57	329.03	18.47							
30	11	133.6	33.58	329.09	18.47							
31	10	121.4	33.60	329.26	18.47	97.90	446.83	0.15049	-2.31%	1.000349	19.432635	0.592284
32	9	109.2	33.63	329.54	18.48	97.90	465.31	0.16222	-2.27%	1.0007731	17.7166553	-0.47039

Square | Evaporation | **Wheel-line** | Crop_data_and_summary | Spatial_data_output | Lateral design | Submain des

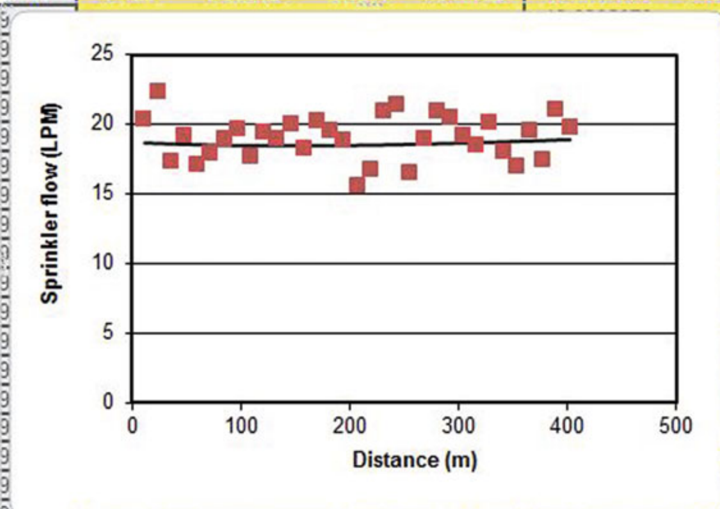

Fig. 14.10 *Wheel-line* worksheet calculations of sprinkler pressures and flows for quarter mile wheel-line with 5/32″ nozzles on 1 % downward slope with 4″ pipe

Example 14.2 Perform an economic analysis with the distribution of application rates predicted with Eqs. 14.5 and 14.6 in order to find the optimal seasonal depth of application for a ¼-mile long wheel-line with 60 ft × 40 ft spacing in a level field. Use the wheel-line parameters in Fig. 14.10. Crop and cost parameters are in white cells in Fig. 14.11. Calculate the cost of energy. The cost of energy is $0.10/kW-hr.

The crop is alfalfa hay. Up to 1 m applied water depth, the yield is 1 metric ton per 12 cm applied depth of water (coefficient = 0.083), which is a linear crop water production function (Sammis 1981). Water applied in excess of 1 m (100 cm in cell G4) is leached. Irrigation water is low in salinity so salinity is not a factor. The value of the alfalfa is $100.00/metric ton.

When the *Wheel line* Button in the *Crop_data_and_summary* worksheet is clicked, the program outputs results to rows 10–17. The average gross depth of application at which maximum profit occurs, 100 cm, is in written by the program to cell K6. Net depth is written to cell K5.

The program is activated by clicking the *Wheel line* button in the *Crop_data_and summary* worksheet (Fig. 14.11). The profits for the range of specified depths in cells C3:C4 in *Crop_data_and summary* worksheet (Fig. 14.11) are output to rows 10–17. The number of columns and rows in the "Square" worksheet is entered into cells C6 and C7. For energy calculations, the seasonal irrigation time is the average application rate divided by the zone flow rate (cell I5 in Fig. 14.10). The program calculates the overall profit (Fig. 14.11, rows 16–17) for a range of average seasonal application rates. The calculated application depths are written to the *Spatial_data_output* worksheet (Fig. 14.12).

The cost of energy per ha is calculated based on the required pressure and volume applied (see Chap. 2). The required inlet pressure is 336 kPa (cell A4 in Fig. 14.10).

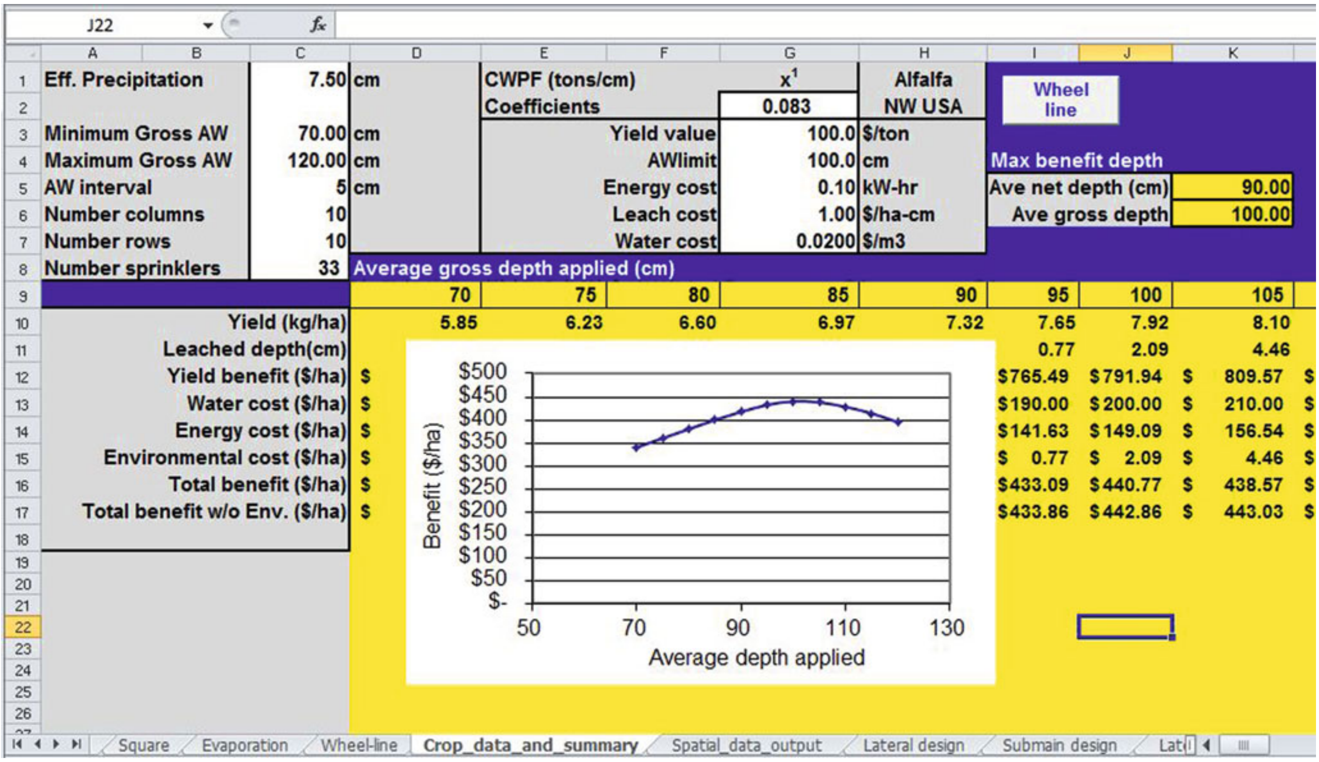

Fig. 14.11 *Crop_data_and_summary* worksheet calculations of costs and profits

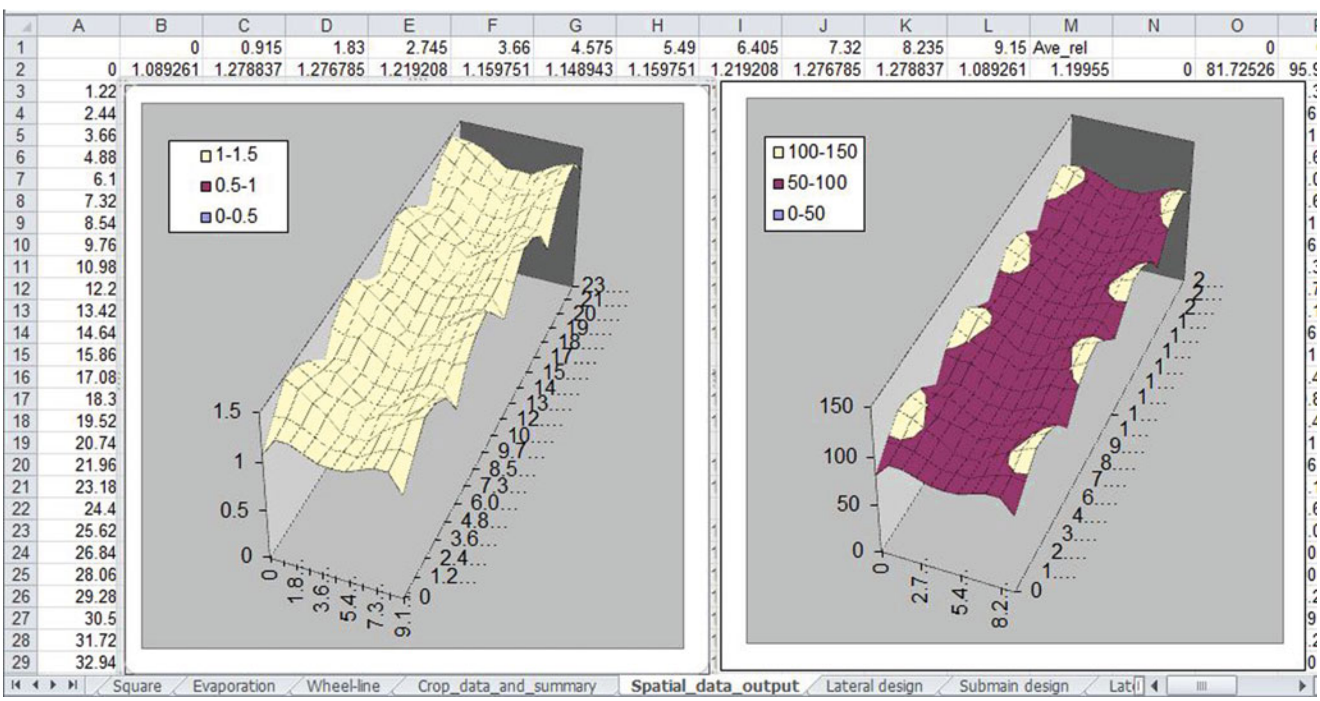

Fig. 14.12 Relative application rates and net application rates along wheel-line

Add the 40 kPa required for pump and fittings and the required pump pressure is 376 kPa (38.3 m). Pump efficiency is 70 %

$$E(kW-hr/ha)=\frac{0.0272\ \ (i_{mm})\ \ (h)}{Eff}$$
$$=\frac{0.0272\ \ (1050\,mm)\ \ (38.3\,m)}{0.7}$$
$$=1,563\ \ kW-hr/ha$$

Thus, energy cost is \$156.30/ha.

The design procedure for hand-lines is the same as for wheel-lines. Hand-lines are generally 30 ft (9 m) sections of 3″ (74.0 mm ID) thin-wall aluminum pipe, with 40 ft (12 m) spacing between hydrants on the main line. Aluminum hand lines are also sold as 20 ft sections of 2″ (48.6 mm ID) pipe. The C value is 90. They generally use a 1/8″ straight-bore nozzle and operate between 40 PSI (276 kPa) and 50 PSI (345 kPa)

Orchard Irrigation with Undertree Sprinklers

Most orchards are irrigated with undertree impacts, rotors, or microsprinklers. Overtree sprinklers on tall risers have fallen out of favor because wetted canopies tend to have disease problems. The fact that trees have large rooted areas reduces the importance of uniform application, as long as each tree receives an equal volume of water. Tree roots are generally deep so deep waterings allow a long period between irrigation events. The difficulties associated with orchard irrigation are that tree trunks block the spray, and that tree spacing constrains sprinkler spacing. Another constraint is that the direction of tractor travel through the orchard may make it necessary to slot sprinklers between trees (Fig. 14.13).

The first question that should be asked during the design process is which direction the farmer farms (drives the tractor). The sprinklers cannot be placed in the path of tractor travel or the tractor will run them over. However, due to slope or other factors, the laterals may need to run in the direction of tractor travel. If so, then the sprinklers must be slotted between the trees as shown in Fig. 14.13. This involves extra work during installation since small trenches must be dug between the location of each sprinkler and the lateral.

Orchards are often constructed on the sides of hills because hills are warmer than low areas: cold air settles in low areas. A cold front in early spring, particularly during bud break, can kill some or all of the buds and eliminate the crop, and the temperature difference between hills and valleys can prevent crop loss. As a result, many orchards are constructed on mild to steep slopes. Except for the steepest slopes, laterals should be run downhill, if possible, in order to maintain uniform pressure. As with other systems, the pipes are sized so that the energy lost due to friction is equal to the energy gained due to elevation. If the laterals run perpendicular to the direction of tractor travel, then sprinklers are placed between trees as shown in Fig. 14.14. An extra sprinkler is generally added to the windward side of the lower line because trees at the windy edge of the orchard tend to dry out.

Diagonal laterals may be convenient for some sprinkler patterns (Fig. 14.15).

Microsprinklers are generally attached to drip tubing that runs along the tree rows in the direction of tractor travel (Fig. 14.16). A Microsprinkler is generally placed near each tree.

One of the original purposes of overtree irrigation, in addition to providing water to plants, was frost protection in early spring. During cold nights, especially during bud break when the new buds are most susceptible to damage by cold, the sprinklers apply water to the plants and the process of water freezing on the plants releases heat and prevents frost damage to the buds. In the northwest United States,

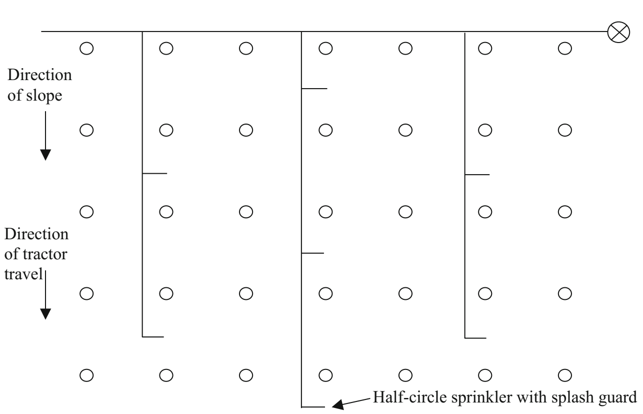

Fig. 14.13 Undertree sprinkler laterals with sprinklers slotted between trees

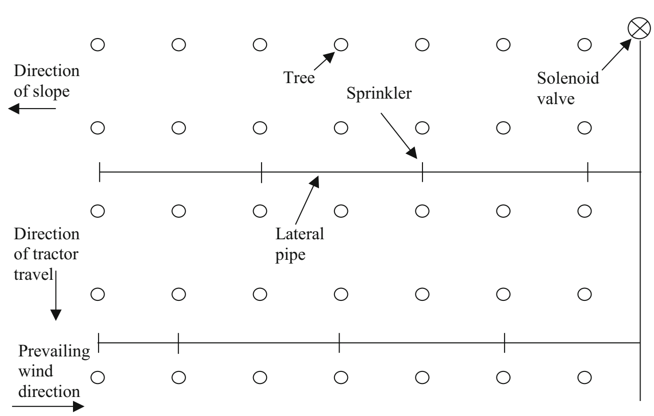

Fig. 14.14 Undertree sprinkler laterals perpendicular to direction of tractor travel

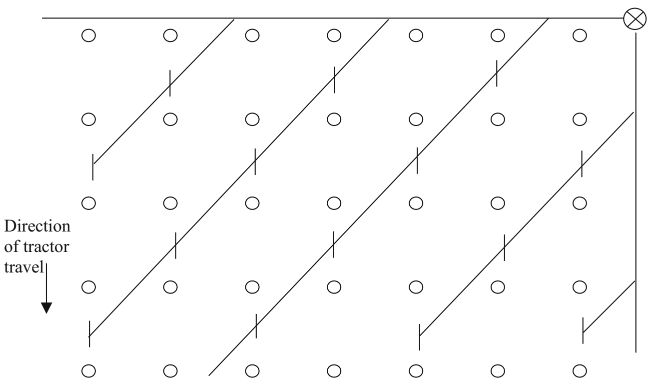

Fig. 14.15 Undertree sprinkler laterals in diagonal direction

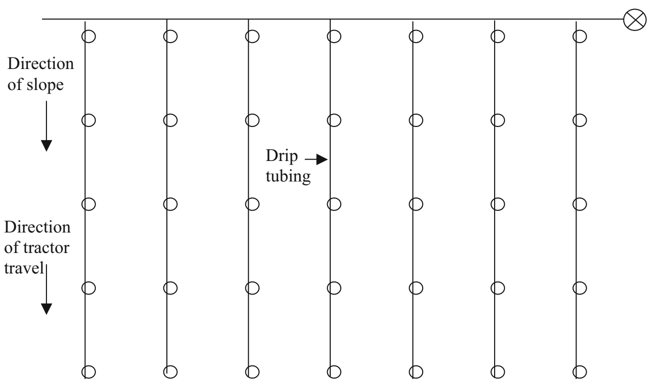

Fig. 14.16 Microsprinkler laterals (drip tubing): microsprinkler placed near each tree

where overtree irrigation was a common practice in apple orchards, a virus in the water damaged the crop when the water was applied directly to the plant. As a result, undertree irrigation is now more popular. Frost protection can still be performed with undertree irrigation because the water freezing on the ground releases heat. In extremely dry climates, the water sublimates directly to the gas phase rather than freezes. Sublimation requires heat so this actually makes the air colder and causes increased frost damage to the buds.

Undertree sprinklers are generally placed on ¾″ PVC pipe risers approximately 18″ (50 cm) above the ground surface. They keep the water below the canopy by using a low angle nozzle. It is also sometimes necessary to keep water spray off the trunk, especially for sensitive trees such as cherries. In this case, a stream splitter device may be attached to the sprinkler in order to deflect the water away from the tree.

If inadequate pressure is available to run conventional straight-bore nozzles, then low pressure nozzles with a hexagonal orifice are an option. These nozzles are designed to work at low pressures in the range of 25–30 PSI (210 kPa).

One challenge with orchard sprinkler design is finding the best sprinkler spacing. For example, trees may be spaced on a 20 × 20 ft (6 × 6 m) spacing and sprinklers have a 30 ft (9 m) radius. If sprinklers are spaced one per tree, then the spacing is 20 × 20 ft and the sprinklers are far closer than head to head coverage requires (capital cost is excessive). However, 40 ft × 40 ft would be much further apart than head to head covering. This may actually be acceptable since the goal is generally to supply each tree with an equal volume of water. Head to head coverage is not as important as making sure that every tree receives the same amount of water. Orchards with a cover crop (grass in the orchard) must be irrigated with sprinklers that wet the entire ground surface; thus, microsprinklers are not acceptable.

In many of the cooler orchard regions irrigated by impact sprinklers or rotors, a typical practice is to have ten zones in the orchard, each of which is watered for 24-hours every 10 days. The systems are designed for peak ET, and then the grower can cut back on the schedule as needed. Orchards watered with microsprinklers must be irrigated more frequently because these sprinklers only wet a fraction of the ground surface. In general, growers prefer a 12-hr or 24-hr irrigation schedule in order to make scheduling more straightforward.

Example 14.3 A cherry orchard with a cover crop in eastern Washington has trees on 18 ft × 18 ft spacing. The canopy height is 5 ft above the ground surface. Maximum soil infiltration rate is 0.3 in/hr (7.5 mm/hr). Peak summer reference ET is 0.3 in/day (7.5 mm/day). The total available water is 8 in (20 cm). The seasonal ET_c is 42 inches (1.06 m). The direction of tractor travel in the field is in the same direction as the 2 % slope. Sprinkler pressure is provided by piped flow from a higher elevation canal. Expected sprinkler operating pressure is 30 PSI (207 kPa). Expected evaporation is 5 %. Leaching is not necessary. Select a sprinkler from the following three options:

L20, 1/8″ hexagonal (low pressure) nozzle, 30 ft wetted radius, 2.58 GPM @30 PSI.

L20, 7/64″ hexagonal (low pressure) nozzle, 29 ft radius, 1.98 GPM @ 30 PSI

LF, yellow nozzle w/ olive green deflector, 35 ft radius, 1.63 GPM @ 30 PSI

The tree spacing dictates that sprinklers can either be spaced at 18 ft × 18 ft, 18 ft × 36 ft, or 36 ft × 36 ft. None of the choices are optimal. The 18 ft × 18 ft spacing is ruled out because of cost.

Because the slope is in the direction of tractor travel, the three possible options are the slotted designs shown in Fig. 14.13 (36 ft × 36 ft) and 14.19 (36 ft × 18 ft) or the diagonal design in Fig. 14.15 (36 ft × 18 ft). The diagonal spacing with one sprinkler every other tree (Fig. 14.15) is preferable because it provides every tree with the same

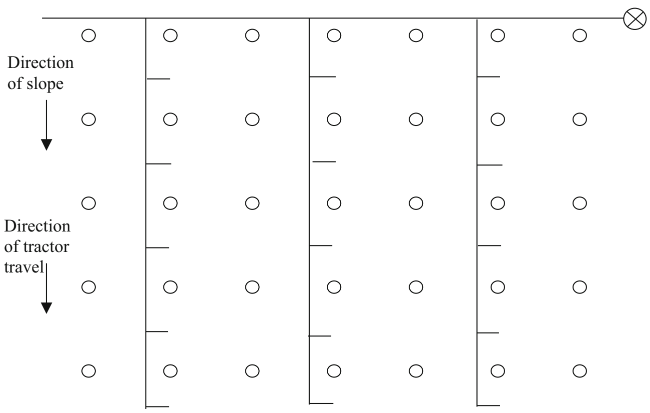

Fig. 14.17 Slotted spacing option for cherry trees

volume of water, unlike the slotted options in Figs. 14.13 or 14.17. We will evaluate the diagonal spacing (water distribution is better) and the 36 ft × 36 f. slotted design in Fig. 14.13 (lower cost).

The diagonal design is evaluated first.

Application rates (diagonal spacing, 18 ft × 36 ft)

The first step is to select the sprinkler and nozzle. For the L20 sprinkler with the 1/8″ nozzle at the diagonal 18 ft × 36 ft spacing, the application rate is

$$di/dt = \frac{(2.58)\ (96.3)}{(18)\ (36)} = 0.38\ \ in/hr$$

Thus the application rate with the 1/8″ nozzle is greater than the maximum application rate of 0.30 in/hr, and this design is not acceptable. Next, try the 7/64″ nozzle.

$$di/dt = \frac{(1.98)\ (96.3)}{(18)\ (36)} = 0.29\ \ in/hr$$

The application rate with the 7/64″ nozzle is just less than the maximum application rate. More investigation of the maximum soil infiltration rate may be advisable since the application rate is close to the specified maximum infiltration rate.

Calculate the application rate for the LF sprinkler with the diagonal 18 ft × 36 ft spacing.

$$di/dt = \frac{(1.63)\ (96.3)}{(18)\ (36)} = 0.24\ \ in/hr$$

Irrigation schedule (diagonal spacing, 18 ft × 36 ft)

From Table 3.3, the MAD for orchard fruit trees is 0.5. Thus, the readily available water is

$$\mathrm{RAW} = \mathrm{TAW\ MAD} = (8\,\mathrm{in})(0.5) = 4\,\mathrm{in}$$

In a 24 hour watering cycle, the expected net application depths for the 1/8″ nozzle and the LF sprinkler are.

$$\begin{aligned}
& \mathrm{i = di/dt(time)(1 - L_e)} \\
(7/64''\ \text{nozzle})\ & \mathrm{i = (0.29\ in/hr)\ \ (24\ hours)\ \ (1 - 0.05)} \\
& = 6.6\ \text{inches in 24 hours.} \\
(\text{LF sprinkler})\ & \mathrm{i = (0.24\ in/hr)(24\ hours)(1 - 0.05)} \\
& = 5.5\ \text{inches in 24 hours.}
\end{aligned}$$

Neither design is acceptable for a 24-hour irrigation cycle because the applied water depth is greater than the RAW. Thus, the farmer would use 12-hour cycles in order to avoid leaching and apply either 3.3 inches (7/64″ nozzle) or 2.75 inches (LF sprinkler).

The reference evapotranspiration rate is 0.3 in/day. Peak K_c for cherries with a cover crop is 1.25 in arid, moderate wind conditions (the climate in eastern Washington in summer). Thus, the peak evapotranspiration would be

$$\mathrm{ET_c = ET_r\ K_c = (0.30)(1.25) = 0.375\ in/day.}$$

$$\begin{aligned}
(7/64''\ \text{nozzle})\quad & (3.3\ \text{in})/(0.375\ \text{in/day}) = 8.8\ \text{days.} \\
(\text{LF sprinkler})\quad & (2.75\ \text{in})/(0.375\ \text{in/day}) = 7.3\ \text{days.}
\end{aligned}$$

Note: only 12 or 24 hour cycles were evaluated because these are generally desired by the farmer. This criterion is not as important if the farmer has hired irrigators that work 24 hours per day or if an automatic controller can accomodate other irrigation set times.

Application rate (slotted spacing, 36 ft × 36 ft)

The L20 sprinkler is not acceptable in this case. It has a 29 or 30 ft radius whereas the sprinklers are spaced 36 ft × 36 ft apart. Thus, trees in the rows between sprinkler laterals would get significantly less water than the rows of trees with sprinklers in the row. The only acceptable design is the LF sprinkler because it has a 35 ft wetted radius.

$$di/dt = \frac{(1.63)\ (96.3)}{(36)\ (36)} = 0.12\ \ in/hr$$

Irrigation schedule (slotted spacing, 36 ft × 36 ft)

In a 24-hr cycle, the depth of application would be 2.75 inches so the number of days between irrigations would be 7 days.

System cost

The slotted design would have much lower pipe, sprinkler, and trenching cost since laterals run directly downhill with half as many sprinklers: 70 % of the diagonal pipe length (cos (45^0) = 0.7).

However, the uniformity is far superior with the diagonal design where all trees receive the same volume of water.

Sprinkler selection

If the farmer chose the diagonal design, then he/she would have to select between the LF and L20 sprinklers. The fact that the LF nozzle requires a 7 day cycle may be attractive because this might make scheduling more straightforward. The LF series sprinklers are better at deflecting water from the tree, which is important for cherry tree survival. Cherry trees are sensitive to sprinkler spray hitting the trunk. As one person familiar with cherry trees said, "Cherry trees spend 20 years trying to die and then they finally do."

Orchard Irrigation with Microsprinklers

Microsprinklers have a relatively small flow rate and wetted diameter. They are placed on stakes with a tubing connection to drip laterals. Their flow rates generally range up to 0.5 GPM (2 L/min), and the diameter of coverage ranges from 10- to 30 ft. Because they have small orifices, canal and pond water must be filtered with sand filters. Well water must be filtered with screen or disk filters. They are not suitable for arid climates because they emit a fine spray or stream, and the small drops evaporate in dry air.

One of the primary users of microsprinklers is the Florida citrus industry. The University of Florida recommends 50–75 % coverage of the soil surface area and has found that greater coverage results in higher yields (Parsons and Morgan 2004). One research project showed that two microsprinklers per tree had higher yields than one microsprinkler per tree (Parsons and Morgan 2004). Depletion levels (MAD) of 25–50 % for microsprinkler irrigation were recommended with lower depletion levels in spring (Parsons and Morgan 2004).

Example 14.4 Citrus grown in a humid climate (Florida) is spaced on 6 m by 4 m spacing. Trees on this spacing have a peak summer water use of 35 L/day/tree. There is no cover crop. Microsprinklers are placed along the row between every tree and have 1.0 L/min flow rate and a 4 m diameter wetted area. Effective depth of rooting is 0.6 m and allowable MAD in summer is 0.25. The AWC of the sandy soil is 8 %. The expected loss to evaporation is 6 %. Assume that the irrigation efficiency is 90 %. Specify an irrigation schedule for this system.

The soil water storage, S, which is the product of RAW and wetted area, can be calculated with Eq. 16.5 (Chap. 16) where D_b is the wetted diameter and Z is root zone depth.

$$S = 780 \quad Z \quad AWC \quad MAD$$
$$D_b{}^2 = 780(0.6\ m)(0.08)(0.25)\left(4^2\right) = 150\ L$$

Calculate the allowable days between irrigations

$$150\ \mathrm{L}/35\ \mathrm{L/day} = 4.2\ \text{days.}$$

Thus, the irrigation system can be run every four days in order to supply the required 35 L/day.

Calculate the length of each irrigation application time

The application flow rate should be adjusted for evaporation and efficiency.

$$\begin{aligned} Q_{net} &= Q_{gross}(1 - L_e) \quad (\mathrm{Eff}) = 1\,\mathrm{L/min}(1 - 0.06)(0.9) \\ &= 0.85\ \mathrm{L/min} \end{aligned}$$

If the irrigation interval is decreased to every two days, then only 70 L must be replaced during each irrigation. The replacement volume divided by the adjusted flow rate is the application time.

Calculate the irrigation run time

$$\begin{aligned} \text{Volume ET/Application rate} &= 70\ \mathrm{L}/0.85\ \mathrm{L/min} \\ &= 82\ \text{minutes.} \end{aligned}$$

Thus, the schedule is 82 minutes every two days or 164 minutes every four days.

Sprinkler Network Design

Chapter 7 showed how to design a single sprinkler lateral. This chapter shows how to design a zone with laterals and a submain. The rule of thumb is that the entire zone should have a pressure variation no greater than 20 %, but strategic use of slopes can result in almost uniform pressure across the zone. As with previous examples in this book, the laterals are designed beginning with the end sprinkler and working backwards. The next step is the submain design. Just as laterals are designed with a k-x curve for sprinklers, the submain is designed with a k-x curve for laterals. This is accomplished by developing a system curve (pressure vs. flow rate) for laterals. As inlet pressure to the lateral is varied, the flow to the lateral varies. Lateral flow rate vs. inlet pressure is plotted, and an exponential equation is fitted to the flow vs. pressure curve.

Example 14.5 An irrigation system has 100 sprinklers arranged in ten laterals with ten sprinklers each (Fig. 14.18). All laterals are 20 m apart and sprinklers are 15 m apart along the lateral. The laterals have a downhill slope of 4 %. The submain has no slope. Sprinklers have a nominal flow rate of 16 L/min at 360 kPa. Minimum acceptable sprinkler pressure is 430 kPa. Gross average depth applied per season is 1 m. Energy cost is $0.10/kW-hr. Friction loss in pump fittings is 4 m. Select pipe diameters and find the required operating pressure and flow rate. The pump curve is:

$$H_{pump} = \left(-5.18{*}10^{-5}\right) Q^2 + \left(8.28{*}10^{-3}\right)Q + 600$$

where

Q = pump flow rate (L/min)
H = pump discharge pressure (kPa)

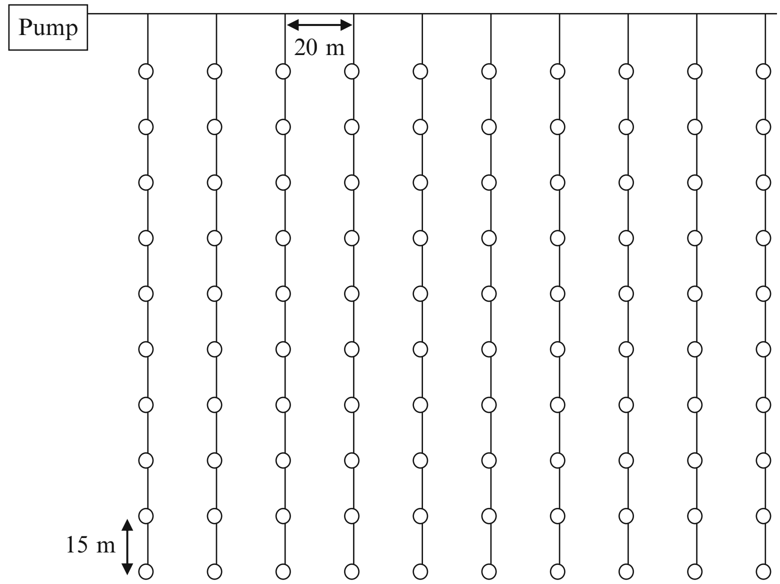

Fig. 14.18 Sprinkler system with 15 m × 15 m spacing between sprinklers

The design is performed in the *Lateral design* and *Submain design* worksheets; however, the following example calculations are given.

The sprinkler k value is calculated based on the nominal flow rate and pressure of the sprinkler.

$$k = \frac{Q}{H^{0.5}} = \frac{16}{360^{0.5}} = 0.843 \quad Q = 0.843\left(H^{0.5}\right)$$

The sprinkler flow rate at the last sprinkler is calculated as follows:

$$Q = kH^{0.5} = (0.843)\ \left(440^{0.5}\right) = 17.69\ \text{L/min} = 0.295\,\text{L/sec}.$$

Pipe pressures are calculated in units of m, the pressure at the last sprinkler is

$$440\ \text{kPa} \rightarrow 440/9.8 = 44.9\ \text{m}.$$

The head loss for 1 in (26.6 mm ID) SCH 40 pipe with pipe length 15 m is calculated:

$$H_L = 1.22{*}10^{10}(15\ \ m)\left(\left(\frac{0.295}{150}\right)^{1.852}/26.6^{4.87}\right) = 0.205\ \ m$$

Next, pressure at the next to last sprinkler can be calculated with elevation and friction loss.

$$H_{n-1} = H_n + H_L + s_L(S/100)$$
$$H_9 = 44.9 + 0.205 + 15\,\text{m}(-4)/100 = 44.5\,\text{m}$$

The *Lateral design* worksheet (Fig. 14.19) allows the user to try different pipe diameters (Fig. 14.19). The worksheet automatically adjusts the number of sprinklers based on the number of sprinklers in cell G6. Diameters are then selected by the user. Because the slope is high, the pipe diameters are relatively small in order to balance elevation energy gain with pipe friction loss.

A submain is similar to a lateral in that it has outlets with flow-pressure relationships. In order to develop an exponential equation for use in the submain design, the "Calculate lateral coefficients" triggers a VBA program that calculates flow vs. pressure data in columns L and M of the Lateral design worksheet. This is accomplished by varying the downstream pressure and recording the inlet pressure and flow rate in columns L and M. This data is then plotted and exponential equation for the lateral flow rate vs. pressure is calculated with Trendline. The lateral flow-pressure equation is shown above the graph ($Q = 6.94H^{0.531}$).

The next step is to design the submain with the lateral equation in the same way that the lateral was designed with the sprinkler equation (Fig. 14.20). The k and x values for the lateral are entered in cells E6 and E8.

The design pressure at the last lateral on the submain is assumed to be the design inlet pressure for the lateral (I24 in Fig. 14.19): 45.0 m. The flow rate into the last lateral is calculated with this pressure (kPa = H_m (9.8)).

$$Q_{lateral-n} = 6.944((45.0)\ \ (9.8))^{0.531} = 176.1\ \text{L/min (see cell G15)}$$

Submain friction losses contribute to the nonuniformity in a zone so it is also important to minimize pressure loss in the submain. In this example, it is more difficult to avoid pressure variation in the submain than the lateral because the submain is on level ground. Pipe diameters are selected in

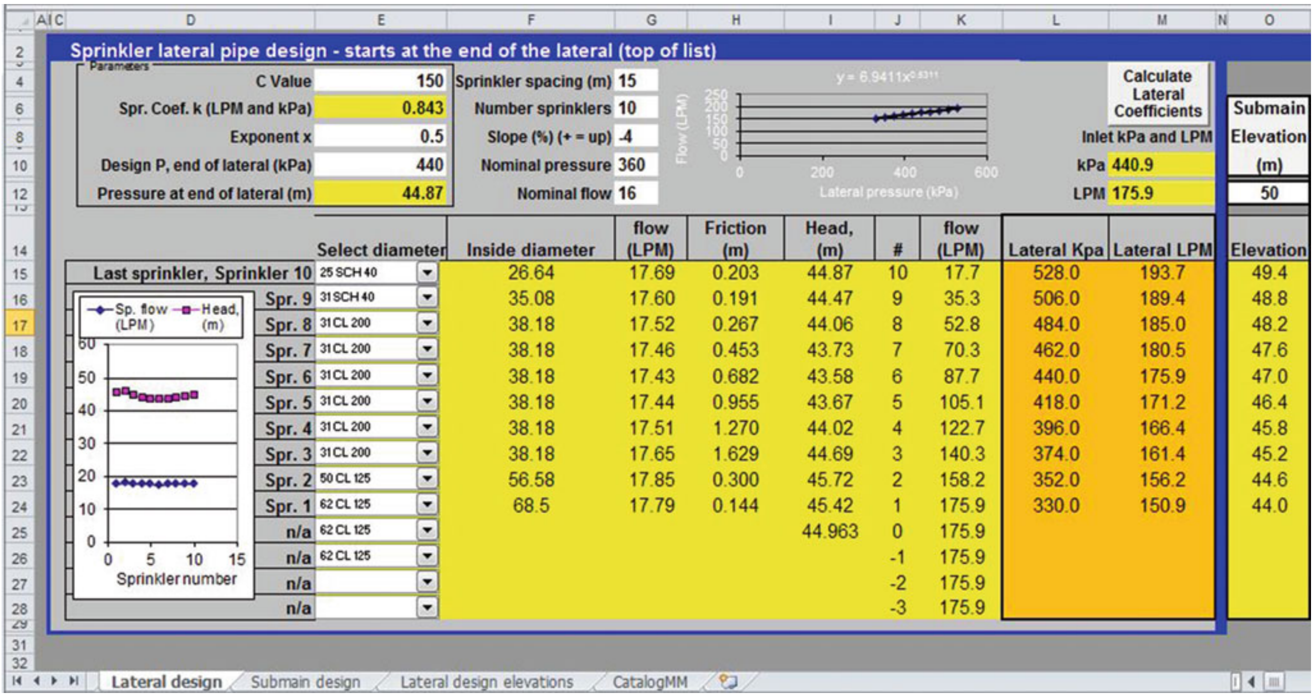

Fig. 14.19 *Lateral design* worksheet

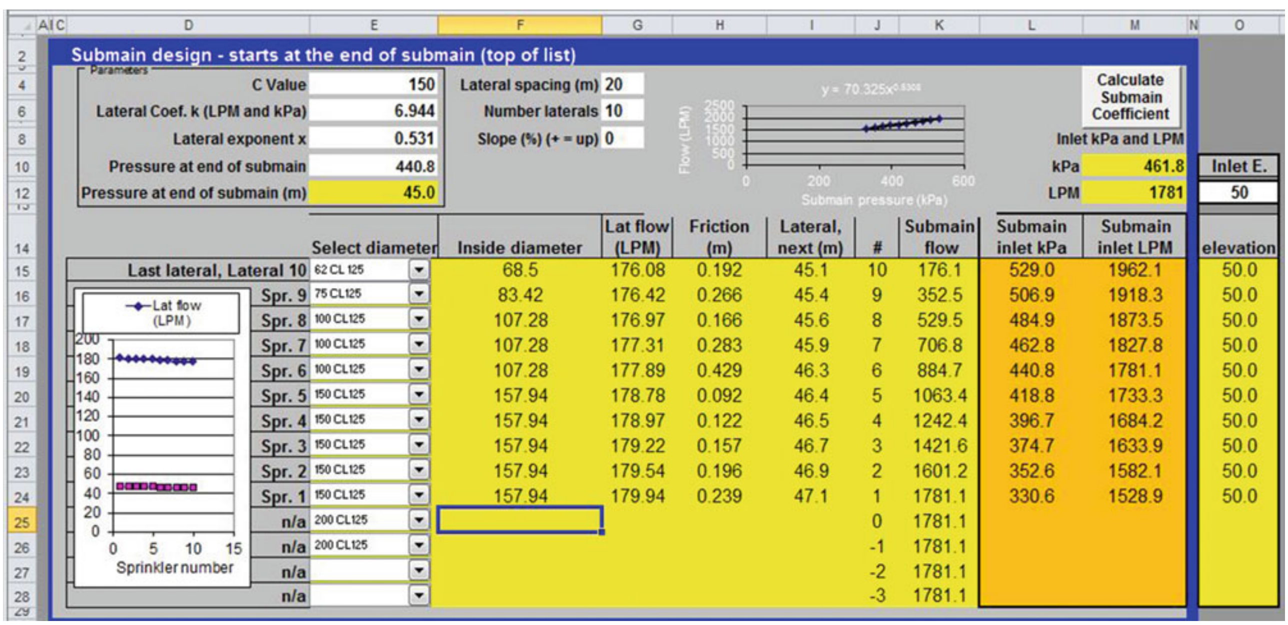

Fig. 14.20 *Submain design* worksheet

order to keep the overall pressure loss low without spending an excessive amount on pipe. There is no quantitative economic analysis in this example (compare present value of cost of energy to capital cost of pipe). For the first section, a diameter is selected, 62 cm (2½″), which results in a reasonably low increase in pressure over the last section, $H_L = 0.192$ m.

The final design results in a pressure at the network inlet equal to 47.1 m. Thus, the pressure difference between the lowest and highest pressure sprinkler is 47.1 m–43.7 m = 3.4 m. Percent pressure variation is 3.4/45 * 100 % = 7.6 %. This results in a sprinkler discharge flow variation across the zone of approximately 4 %. As shown in previous examples, the variation due to sprinkler application pattern variability would be much higher than the variability due to 4 % sprinkler flow variation.

From an energy standpoint, there is a cost to the pressure variation because the system could operate at a lower pressure without the pressure variation. The cost of the pressure variation is the product of the pressure loss and the volume applied. The pressure loss is 3.8 m, the seasonal gross depth applied to the field is 1 m, and the pump efficiency is 80 %. Thus, the total cost of this energy loss is calculated as follows:

$$E(kW-hr/ha) = \frac{0.0272\ (i_{mm})\ (h)}{Eff} = \frac{0.0272\ (1,000)(3.4)}{0.8} = 115\ \ kW-hr/ha = \$11.5/ha/season$$

As with the lateral, a system curve is generated in the upper right corner of Fig. 14.20 for the submain by clicking the *Calculate Submain Coefficient* button:

$$Q_{system}(L/min) = 70.3\ H^{0.531}$$

The intersection of the pump curve and the system curve is the operating point for the pump. If 4 m head (40 kPa) is lost in pump valves and fittings at the pump station, then the system curve must be adjusted to account for this pressure loss. This is not the same as the 3.8 m head loss in the pipe network.

$$Q_{system}(L/min) = 70.3\left(H_{pump}-40\right)^{0.531}$$
$$H_{pump}(kPa) = \left(Q_{system}/70.3\right)^{1/0.531} + 40$$

where

$$H_{pump} = \text{pump discharge pressure, kPa.}$$

Substitute the submain equation into the pump equation since $Q_{system} = Q_{pump}$.

$$Q = 70.3\left(\left(-5.18{*}10^{-5}\right)\ Q^2 + \left(8.28{*}10^{-3}\right)Q + 600 - 40\right)^{0.531}$$
$$0 = (70.3)\ \left(-5.18{*}10^{-5}\right)\ Q^2 + \left(8.28{*}10^{-3}\right)Q + 560)^{0.531} - Q$$

The root of this equation is Q = 1,734 L/min. Thus, the pump operating pressure is

$$H_{pump} = \left(-5.18{*}10^{-5}\right)\ \left(1,734^2\right) + \left(8.28{*}10^{-3}\right)(1,734) + 600 = 459\text{ kPa}$$

If H_{pump} is 459, then H_{system} is 459–40 = 419 kPa

The calculated intersection point is shown in Fig. 14.21. The same solution is found with the iterative technique in the *System and pump curves* worksheet.

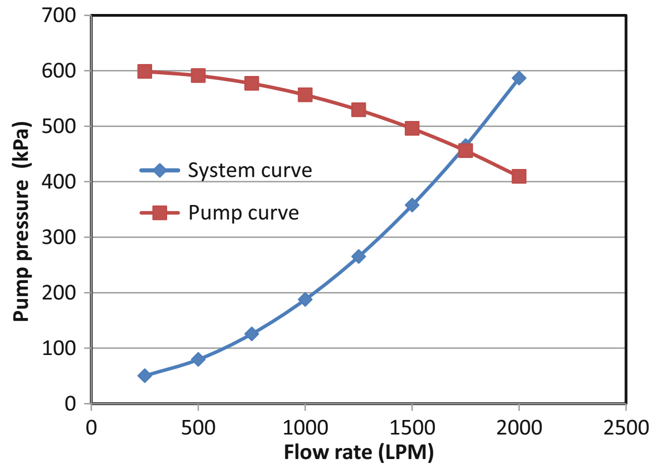

Fig. 14.21 Pump curve and system curve for Example 14.5

$$Q_{system}(L/min) = 70.3(419)^{0.531} = 1,735\text{ L/min}$$

Questions

1. An orchard is on a hill. How should the mainline, submain, and laterals be positioned so that all the sprinklers on the property have nearly the same operating pressure?
2. True or false. The two main causes of nonuniformity of application in wheel-line sprinkler systems are hydraulic variation along the pipeline and spatial variability of soils.
3. True or false. Water hammer is a major problem in sprinkler laterals.
4. The last two sprinklers on a PVC pipeline have a flow rate of 20 L/min. The end pressure is 350 kPa. The distance between sprinklers is 15 m. The slope is 3 % downhill. Select pipe sizes for the last two pipe sections so that the three sprinklers have no more than a 0.2 m variation in head between them. Use a Hazen-Williams C value of 150. You can use the Worksheet to find the pipe sizes, but also make the two calculations of pipe pressure losses and change in pressure from one sprinkler to the next by hand.
5. A ¼ mile wheel-line has a downhill slope of 2 %. Use 3/16″ nozzles (ID = 4.8 mm). Calculate an equation for sprinkler flow rate vs. pressure. Then, determine whether pressure would have less variation with a 4 in (97.9 mm) or 5 in (123 mm) pipe.
6. For the parameters in Example 14.2, calculate the seasonal depth of water application at the last sprinkler, 6.1 m row position, 0 m head position. Then calculate the depth of water application at the 2.4 m row position,

0 m head position for the first sprinkler. Are these the extremes of application depth? What is the percent difference between the maximum and minimum application rates? The average seasonal depth of water application to a field is 75 cm. Calculate the application depths at the maximum and minimum positions. Evaporation rate is 10 %.

7. Redo Example 14.2, but don't offset the wheel-line positions with respect to the hydrants. Compare the total profit, and the optimal depths with those found in Example 14.2. Recalculate the pump power and the average depth applied as in Example 14.2.
8. Redo Examples 14.1 and 14.2, but use handlines. The normal design for handlines is 40 ft along the mainline and 30 ft between nozzles. Select a nozzle and flow rate from catalogs at the following web sites. The length of the run is 1/8 mile long and the handlines use 3″ aluminum pipe. The slope is 0.005 m/m in the downhill direction. Use the same evapotranspiration, precipitation, power, and production functions as in Example 14.2. Don't offset the handlines. Select sprinklers based on catalog data below. Show the variability due to hydraulics and variation in wetting due to sprinkler patterns. Maximum application rate in 0.3 in/hr. Operate the handlines at 45 PSI pressure.
   http://www.rainbird.com/ag/products/impacts/30H.htm
   http://www.rainbird.com/documents/ag/chart_20JH.pdf
9. Redo Example 14.3 with 14 ft by 14 ft tree spacing. Leave all other parameters the same.
10. Calculate a microsprinkler irrigation schedule for an orchard with 4 m × 3 m tree spacing and microsprinkler spacing. Each tree has a peak summer water use rate of 25 L/day. Microsprinklers have a 0.7 L/min flow rate and a 3 m diameter wetted area. Rooting depth is 1 m and allowable MAD is 0.35. The AWC is 12 % for a sandy loam soil, the expected loss to evaporation is 12 %, and the irrigation efficiency is 90 %. Specify an irrigation schedule for his system.
11. Repeat Example 14.5, except use 12 laterals by 12 sprinkler geometry, and the pump curve is $H = -5.18*10^{-5} Q^2 + 0.00828 * 10^{-3} Q + 900$. Find the operating point of the system

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